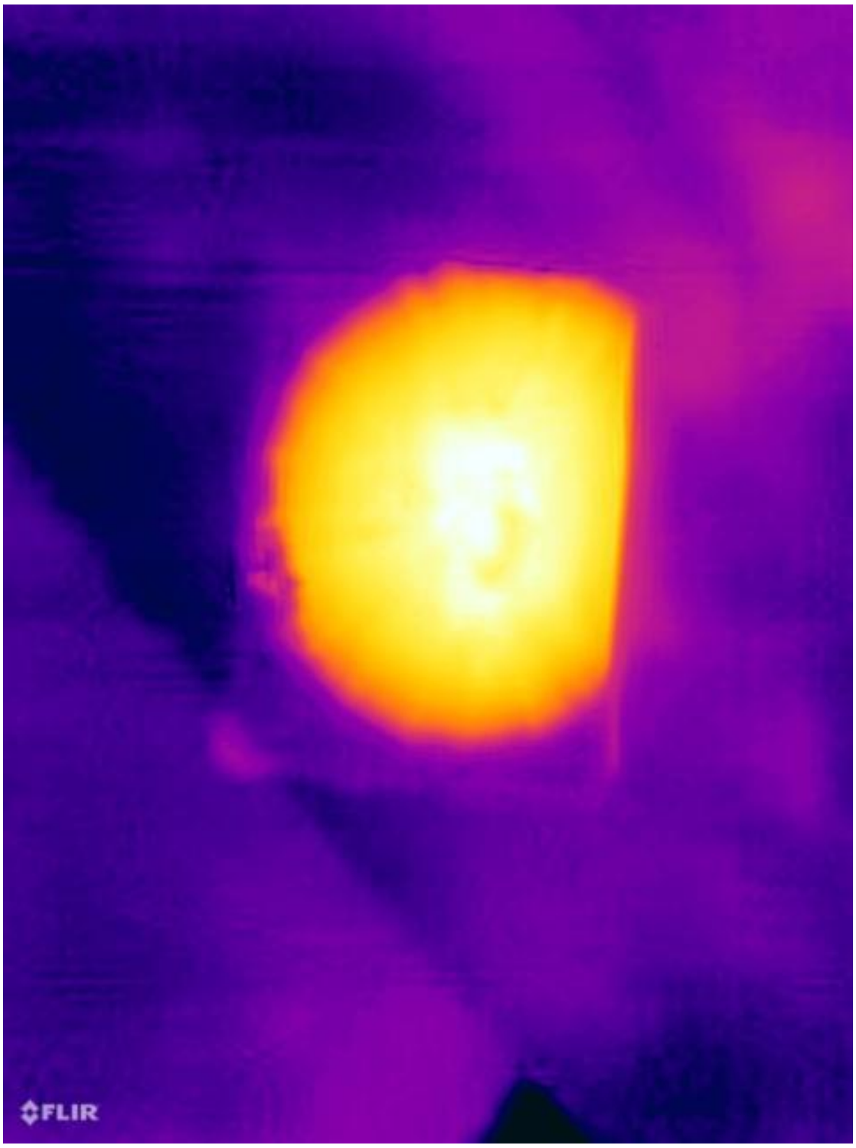
HEAT PADS AND SUPERCOOLED WATER

STUDENTS INVESTIGATE UNDERCOOLING USING HEAT PADS AND SUPERCOOLED WATER.

Mojca Čepič

University of Ljubljana, Faculty of Education, Slovenia



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SUITABLE FOR AGE(S)	SUBJECT(S)	KEY FOCUS
12 - 18 years	Physics, Chemistry	Designing investigations Conducting investigations

INTRODUCTION

This task examines the phenomenon of undercooling, a state in which a liquid remains in its liquid phase even below its normal freezing point. By exploring heat pads and supercooled water, students observe and analyse first-order phase transitions in an engaging and interdisciplinary context.

Heat pads are filled with material that is crystalline at room temperature and is liquid at the regular boiling temperature of water, with the transition temperature slightly above 50˚C. However, the material is easily supercooled, and once it is heated above its melting point, it remains liquid at room temperature or even lower temperatures. This makes it a "carry-around heater" that doesn't require fire or electricity. Students inquire about the phenomenon. The task is extended to undercooling the water below its melting point, to expand the inquiry to water, and to compare and identify similar characteristics between both experiments.

The aim of the task is for students to get familiar with a phenomenon that is always associated with first-order transitions between solids and liquids. The goal is not just to demonstrate a physical effect, but to offer a real-world, inquiry-driven approach to thermodynamic concepts such as latent heat, specific heat, and phase changes.

The task is suitable for the upper secondary level, when thermodynamics, including states of matter and phase transitions, is taught. In lower secondary, it could be used to enhance experimental skills, such as controlling variables, measuring temperature, and similar activities. Additionally, in lower secondary school, the activity is introduced when states of matter and phase transitions are discussed.

TASK DESCRIPTION

The task explores two cases of undercooling:

1. A commercial heat pad, usually used for heating sore parts of the body or cold hands in winter. which contains a supercooled liquid that crystallizes upon mechanical stimulation, releasing heat. To activate the heat pads, immerse them in boiling water until the contents become gel-like. The contents retain their appearance after cooling, but with a sharp blow on the pad or by bending and releasing the stick or button inside, the contents suddenly crystallise and heat up considerably.
2. Distilled water cooled below 0°C, which remains liquid until disturbed and then freezes suddenly with an accompanying temperature rise. A situation occurs when if one leaves a bottle of water outside on a cold winter night, it sometimes does not freeze. The water in the bottle remains clear. However, when you pick up or move the bottle, the water suddenly becomes opaque, filled with small

flakes floating throughout. Upon inspecting these flakes, it turns out they are formed of small conglomerates of ice full of water.

Both cases represent first-order phase transitions, illustrating the latent heat effect in a vivid and measurable way. Students work in groups and follow an inquiry-based learning (IBL) cycle. experimentally established conditions for observation of both phenomena are the focus of this task.

Students should realise that a very similar phenomenon can usually be interpreted as one single phenomenon with a single explanation of the chemistry or physics behind it. In this case, both materials are supercooled, and when they start to crystallise, they both warm up. The difference lies only in the temperature at which the phenomenon of sudden crystallisation occurs and ends.

Students develop their observation skills, are trained in planning, drawing conclusions and reporting. Additionally, in upper secondary school, the released heat and the heat capacity of the heat pad containing liquid can be measured using a standard procedure. The temperature of the heat pad, in which crystallisation has just finished, is measured, and the pad is placed in a calorimeter with a well-defined volume of water. The temperature of the water is measured before and after. The quantity of heat transmitted to water is measured, and the whole heat released during the process is calculated by extending the temperature difference to the initial temperature of the pad before crystallisation.

The task connects teaching and learning in chemistry and physics. Thermodynamics is a common link between the two, but here, the teacher of both subjects can analyse the same phenomenon and incorporate the experience into the teaching of chemistry and physics topics later.

TASK PREPARATION

The task requires familiarity with thermodynamic concepts, including the liquid and solid phases of matter, melting temperature, latent heat, and specific heat. Students become familiar with a new phenomenon that is usually not included in the curriculum: overcooled material. However, as the task is relatively simple, it can also be used as a traditional laboratory to measure the thermodynamic properties of heat pads, accompanied by an interesting and motivational phenomenon. If experimental skills such as controlling experimental conditions or observation are the focus of the activity, it could also be used at the lower secondary level in science lectures, or its subjects, chemistry, and physics.

Materials needed:

Equipment Per Group:

- 1–2 transparent heat pads, pre-activated or in liquid state [Heat pads have to be prepared in advance, that is, "cooked" in boiling water until every remaining crystal disappears, about half an hour or even more, and then cooled down to room temperature. If heat pads are new and the content is in the liquid state, they can be used directly].
- A glass beaker or cup (≥ 200 mL)
- Regular or digital thermometer

- Clean eprouvette (test tube)
- Access to an infrared thermometer (can be shared)

For All Groups:

- Ice cubes (sufficient for all experiments) [the supply of ice should be big enough to fill all the glasses when needed]
- Salt (large grain preferred)
- Alcohol and cotton wool or alcohol wipes (for cleaning thermometers)
- At least 1 L of distilled water
- Infrared camera (optional but highly recommended)

Optional but Useful:

- Video recording devices (e.g., smartphones) for student documentation
- Visuals from an infrared camera to demonstrate heat evolution during crystallization

The task can be regarded as structured because students encounter the phenomenon of undercooling for the first time. Therefore, they need to become familiar with the details of the phenomenon, including how crystallisation is initiated, which properties change during crystallisation, and how. It is crucial that at least the initial part of the activity is structured. However, even when studying the same phenomenon for water, the experimental part involves several subtleties, so it is preferable that the entire activity is structured. Experiments are still very interesting and surprising, and teacher guidance helps ensure the experience takes place within the limited time usually available.

TASK IMPLEMENTATION

Brainstorming starts with discussing unpleasant feelings, when it is cold, and we have to warm up ourselves. What are potential actions to become warmer?

Possible answers are usually, to add another layer of dresses, to light a fire, to go inside, where it is warm, and hopefully one or even more students report an experience with heat pads, either from skiing or from physiotherapy. If the teacher is lucky, the student should describe the experience. If not, the teacher introduces the magic "heat in the pocket". Shows the heat pads and tell the students that they are at the heart of today's inquiry.

An introductory experiment, which provides experience

Each group gets one heat pad. Students are encouraged to touch it, to measure its temperature, then the teacher shows how to initiate the crystallisation process. Each head pad has either a stitch or a metal button-like object inside, which has to be bent and released.

Students observe crystallisation of the material, they are encouraged to touch the pad, when crystallisation stops, they measure the temperature of the head pad and compare this temperature with other groups.

Groups at this point articulate their observation in a form of a sentence or two and a possible sketch of the experiment. The teacher asks groups to report or to add their comments on reports of other groups if they believe anything is missing.

In the next part, the activity is repeated. The teachers either show the movie prepared with an infrared camera or shows the sequence of pictures taken with an infrared camera during the crystallisation available here as a supplementary material and discusses the process. If there are enough pads available, students should repeat the experiment, as they are usually able to see more details the second time, when they already know what will occur and what to observe. After the repetition, students could correct or improve their notes and the teachers discuss the observations once again.

The teacher resumes final conclusions and takes care that information is written in students' notes.

An example of a good note

"The heat pad is initially cool, at room temperature. When the stick is bent and released, the crystals start to form and the heat pad warms up so much that it is very hot to the touch. The content remains crystalline even when cooling down. The final temperature of the crystalized pads was similar in all groups."

Here, at this point the activity could be finished, the physics behind explained, or it can be extended to another quick, but not so straightforward activity, the supercooled water.

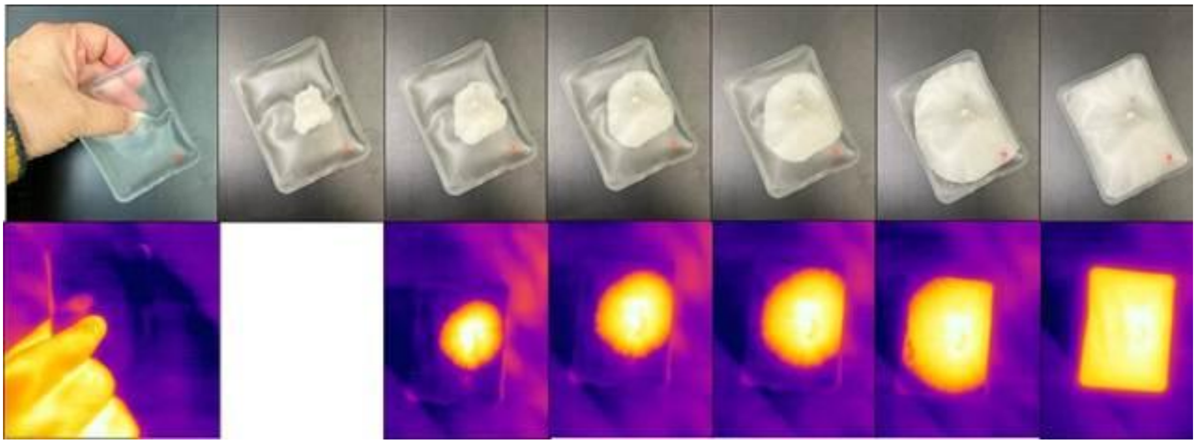

Figure 1: Crystallisation of the content of the heat pad. The crystallisation takes a few seconds only. (Below) The same phenomenon photographed by infrared camera. Two different pads were photographed with a regular and an infrared camera, and the photos are aligned for approximately the same phases of crystallisation.

Students get glasses with ice cubes, they add one full big spoon of salt or event two, they mix the ice cubes with salt. The ice cubs start to melt quickly, and the crystals of ice are formed on the outer side of the glass indicating that the temperature of the mixture should be below the melting temperature of water. The temperature is measured with a regular alcohol thermometer, or even better, with a digital thermometer. Temperatures of the mixture are usually about -10˚C or even lower. The phenomenon is called cryoscopy and is discussed in (Čepič, 2023), where also a few interesting experiments are suggested.

The eprouvette is filled with distilled water. The level of water should be about 5 cm above the bottom of the eprouvette, not more. The thermometer is thoroughly cleaned with alcohol, dried in air, and inserted into the water in the eprouvette. The eprouvette with the thermometer is inserted to the glass with salted ice, and the reading of the temperature is observed. Students should be warned not to touch or move the glass, as any disturbance can change the outcome.

If the experiment runs well, the temperature of water in the eprouvette is slowly decreasing. The decrease does not stop at 0˚C, when the water should start to freeze, but decreases further. When the temperature reaches -4˚C, students carefully remove the eprouvette from the glass and there should still be water in the liquid phase. If the thermometer is stirred a little, the content suddenly becomes cloudy, and the temperature increases to 0˚C.

Comments to the second experiment

The water, the eprouvette, and the thermometer should all be very clean. Any piece of dust or dirt can cause crystallisation at higher temperatures, that is, close below 0˚C, which makes the phenomenon impossible to observe.

In principle, the water can be supercooled to -80˚C, however in this very simple classroom experiment, the water suddenly freezes at a much higher temperature. Several years of experience indicate that one cannot really predict to which temperature one could wait to observe the crystallisation process. However, temperatures between -4 ˚C and -6˚C are usually relatively safe. If students really have to wait longer, they have to observe the thermometer carefully. If the temperature suddenly increases to 0˚C, the crystallisation has already happened and the opportunity to observe it is lost for the round. The whole experiment should be repeated.

To repeat the experiment, we suggest either to use a new clean eprouvette and a fresh distilled water, or to wait until the water in the eprouvette melts completely. Do not remove the thermometer, just wait until the water is clear again. In this way we limit the possibility of getting any dirt into the water, which could speed up crystallisation.

The teacher must ensure that all students have observed crystallisation, either through their experiment or by showing them a movie afterwards. Usually, students are prepared in the second experiment, they make movies on their mobile phones, and they are happy to share them. There are movies found on the internet, for example (YouTube 2007, 2010)

At this point, the groups compare both phenomena, that is, crystallisation of the liquid in a heat pad and the freezing (actually, the crystallisation) of water. Depending on comparison students made, the teacher poses additional questions, like

- ***What was the state of matter at the beginning and at the end of the observation?***

  At the beginning the state of matter is in both cases liquid, heat pads are full of crystals at the end, water has pieces of something that might be ice, but is also full of water as a sponge. Taking it out and squeezing the water out, looks like wet snow.

- ***What was the temperature at the beginning and at the end of the observation, semi-qualitatively or in explicit numbers?***

  In both cases, the temperature at the beginning was lower; at the end of the experiment, when the matter is crystallised, it is higher.

- ***What is similar in both phenomena?***

  See above.

- ***What is different in both phenomena?***

  The appearance of the material differs, and the temperatures at which the crystallisation starts and finishes differ.

KEY LEARNINGS

This task was tested during the local multiplier event in 2022 in Ljubljana by a group of 20 teachers. Besides parts of the task, the undercooled water was carried out at several workshops with in-service teachers in Slovenia and in Bosnia. It was found that:

CONCLUSION

This task introduces the phenomenon of undercooling using easily available heat pads. The task is relatively quick and can be divided into two quick experiments, one with the heat pad and another with water, in different lectures. In this way, the teacher enriches the relatively boring topic of phase transitions and energy considerations related to them.

At the upper secondary level, the task can be developed into laboratory exercises to determine the released heat during the crystallisation process and the specific heat of the heat pad content. Calculations could enrich the task, for example, what was the mass of the ice that froze suddenly?

The supercooling aspect was motivated by Gianino's 2007 paper. Heat pads were added later, as they allowed for easier study and are more reliable for introducing the phenomenon.

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APPENDIX

Why can materials be supercooled?

Phase transition between two different phases can be discontinued or the first order, or they can be continued or the second order.

The first order, discontinuous, transitions from liquid to solid or vice versa are common in everyday life. First order transitions are always associated with the latent heat. The latent heat is released when the material solidifies (freezes), and it is absorbed, when the material liquifies (melts). Both processes, freezing and melting occurs at the same temperature. An example is water, which freezes and melts at 0˚C, providing the water is not supercooled. But the same is true for the content of the heat pad or for metals.

Continuous transitions are rather rare, but they can be found in exotic materials like liquid crystals or superconductors for example. Characteristic for them is that at a well-defined temperature, new properties of the matter start to exhibit, for example, superconductivity. There is no latent heat absorbed or released at that temperature.

There is a third type of the transition, one often meets in everyday life, and this could be called, no transition at all. The properties characteristic for the solid and for the liquid phase continuously develop one to another. For example, wax, butter, or cheese becomes softer and softer as the temperature increases until it becomes liquid. However, one cannot determine at which temperature the vax, butter, cheese are already a liquid.

The first order transitions between liquids and solids can undergo the undercooling, but the reverse, the overheated crystal is not possible. The reason is the following. The binding energy between molecules as a group, the reason for the surface tensions and the reason for the crystalline structure, has two minima. One minimum corresponds to disordered liquid, and molecules are happy in it, another to ordered solid, and molecules are also happy in it. But in which of the two molecules are happier? At higher temperatures above the melting point of the crystal, the molecules are in a disordered liquid state. At very low temperatures, molecules are happy in an ordered crystalline state, but they cannot form a liquid state. Below the melting temperature, there is a grey zone where both states are possible simultaneously. During the freezing molecules gradually arrange in a crystalline pattern. A molecule, which is initially found in a favourable surrounding of disordered neighbouring molecules, moves across non favourable positions and finds its favourable position in a crystal. For this movement across non favourable positions, the molecule needs enough energy. If there is no energy, the liquid can become calmer and cooler, but the system cannot organise in a crystalline structure. The energy is added by a released bent stitch in the heat pad, or by stirring the supercooled water; some molecules gain enough speed to overcome unfavourable positions and occupy a favourable position in the crystal. As the molecular bond in the crystal is stronger, its energy is more negative, the energy is released. This released energy allows other molecules to jump from disorder to order and the process speeds itself up. As a side effect, the material heats up due to the released energy. To maintain freezing this energy should be taken away by cooling. But let us say we do not cool the sample. How high the temperature rises because of released heat during the sudden freezing of supercooled water, gel in the pad? As molecules in the crystals are bound with interactions to their neighbours, they also vibrate around their favourable positions due to thermal fluctuations. However, on the surface of the crystal, molecules have less neighbours holding them, and they break their bonds more easily and join the liquid state. This is the process of melting, for which the latent heat should be added to break the bonds at the surface gradually. But this is also the reason that one cannot overheat the crystal. When thermal fluctuations are strong enough to break surface bonds, the crystal gradually melts. The temperature when this happens is called the melting temperature. Therefore, the temperatures of pads were also very similar, slightly above 50˚C, when they have crystallised.

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