Reasoning with thermal cameras

Framing and meaning-making in naturalistic settings in higher education

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Abstract

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In this Licentiate thesis, framed by the Resources framework and Social semiotics, I explore how students and instructors, investigating thermal phenomena with *IR cameras*, come to *conceptually* and *epistemologically frame* the *naturalistic settings* they participate in. Additionally, I look at how they employ *resources* in a *productive* way, what *barriers* they encounter while reasoning about the thermal phenomena and how the *semiotic resources* of the IR camera relate to the framing and resources employed in their investigations. The thesis is based on three groups of participants: two chemistry engineering students and their two lab instructors (PhD students) in a calorimetry lab part of a unit on thermodynamics in a chemistry introduction course, and primary school teacher students in a physics unit on thermodynamics that is part of a course on science. The engineering students and their instructors were studied in a chemistry lab involving the Born-Haber cycle and enthalpy change of solution for some salts. The primary school teacher students were studied in a classroom where they had just had a class on heat transfer. Data was collected through video recording and subsequently transcribed. The analysis is qualitative and contextual and is mainly based on multimodal conversation analysis with a special focus on the types of talk used and the resources employed, through the concepts and examples used by the participants when they are investigating a thermal phenomenon.
The thesis contributes with situated knowledge claims that include:

- that the semiotic resources of an IR camera afford attention to thermal aspects (red, white and blue), measurement (the temperature values) and spatial movability (the form of the camera). The colors of the camera and the temperatures affect the conceptual framing (the students use of the concepts of heat and temperature) and the numbers and form affect the epistemological framing (what they do and how they do it). Other aspects affecting the two types of framing are also found.
- that given a sequence of anchoring situations and experiments and some chosen teaching content, if the situations share some common teaching content and are sufficiently proximate, it is possible for the participants to conceptually frame the sequence in a coherent way.
- that both disciplinary and everyday based resources may act as both barriers and productive resources within the same reasoning process.

In addition, some productive resources and/or barriers in the reasoning processes are identified for each of the three groups.

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Till Caspian, Nemo, Tova och LärNat

List of peer-reviewed papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Samuelsson, C.R., Elmgren, M., Haglund, J. (2019) Hot vision: Affordances of infrared cameras in investigating thermal phenomena. *Designs for Learning, 11*(1), 1-15

Author's contribution: I carried out the data collection, transcribed the data, made the initial analysis, continued with later iterations of transcription and analysis (after discussions with co-authors), wrote the initial draft and the final, published version (the draft was sent between the authors multiple times inbetween these two stages).

II Samuelsson, C.R., Elmgren, M, Xie, C., Haglund, J. (2019) Going through a phase: Infrared camera in a teaching sequence on evaporation and condensation, *American Journal of Physics*, *87*(7), 577-582

Author's contribution: I suggested and designed the final sequence (adding experiments suggested by other researcher and/or co-authors), carried out the data collection, transcribed and analyzed the data (data sessions and discussions with co-authors inbetween iterations of transcription and analysis), wrote an initial draft and the final version (the draft was sent between authors inbetween these two stages).

Reprints were made with permission when necessary from the respective publishers.

Other supporting work

Conference presentations

Samuelsson, C., Haglund, J., Elmgren, M. (2019). *Adding salt to ice: Exploring students' cognitive resources.* In: Teknisk-naturvetenskapliga fakultetens Universitetspedagogiska Konferens 2019, Uppsala, Sweden, March 19, 2019

Samuelsson, C., Haglund, J. (2018). *Using infrared cameras in physics and chemistry education.* In: Gordon Research Conference - Physics Research and Education, Bryant University, Smithfield, RI, US, 10 - 15 July 2018

Samuelsson, R., Elmgren, M., Haglund, J. (2018). *Going Through a Phase.* In: The Gordon Research Seminar on Physics Research and Education, Smithfield, June 9-10, 2018

Samuelsson, R., Elmgren, M., Haglund, J. (2018). *Phasing the invisible.* In: Forskning i Naturvetenskapernas Didaktik, Malmö, November 7-8, 2018

Samuelsson, C., Haglund, J., Elmgren, M. (2017). *Looking for solutions: University chemistry and physics students interacting with infrared cameras.* In: ESERA 2017, Dublin City University, Ireland, 21-25 August

Samuelsson, R., Haglund, J., Elmgren, M. (2016). *Hot vision – affordances of infrared cameras in education.* In: The 8th International Conference on Multimodality, University of Cape Town, South Africa, 7-9 December, 2016

Samuelsson, R., Haglund, J., Elmgren, M. (2016). *Användning av värmekameror vid öppna laborationer.* In: Forskning i Naturvetenskapernas Didaktik, November 9-10, 2016, Falun

Contents

1. Introduction 19
    1.1 Thermodynamics and education 19
    1.2 The scope of the knowledge claims 22
    1.3 Structure of the thesis 22

2. Theoretical framework 24
    2.1 The learning perspectives 24
    2.2 Knowledge as pieces or resources 25
    2.3 Other resources 28
    2.4 Knowledge as meaning 29
    2.5 Making meaning through talk and interaction 32

3. Literature review 37
    3.1 PER 37
        3.1.1 American PER 37
        3.1.2 Three American frameworks 39
        3.1.3 European PER 41
        3.1.4 Some European frameworks 41
        3.1.6 CER & PER 42
    3.2 Learning of thermodynamics 44
        3.2.1 Thermodynamics as a physics topic 45
        3.2.2 Energy as a cross-cutting concept 48
        3.2.3 Students' understanding of heat 49
        3.2.4 The role of personal and embodied experiences in learning about heat 51
        3.2.5 Ways of teaching about energy transfer and transformation 53
        3.2.6 The role of contexts, framing and resources in thermodynamics education 55
        3.2.7 Productive resources 61
        3.2.8 Barriers to learning thermodynamics 67
        3.2.8 My research and "thermodynamics education" 72
    3.3 Technology for visualizing natural phenomena 73
        3.3.1 Dynamic visualizations, simulations and MBLs 73
        3.3.2 Infrared (IR) cameras 77
    3.5 Situating my own research 82
        3.5.1 Research questions 88

4. Assumptions from theory and literature review....89
4.1 Assumptions based on themes found in the literature review....89
4.2 Assumptions based on theory....90

5. Methodology....92
5.1 Naturalistic inquiry....92
5.2 Prediction-Observation-Explanation....96
5.3 Data collection....99
5.6 Multimodal conversation analysis....102
5.7 Trustworthiness....104
5.8 Ethics....108

6. Results....110
6.1 Paper I....110
6.1.1 Context....110
6.1.2 The data....111
6.1.3 Transcription....112
6.1.4 Analysis and discussion....113
6.2 Paper II....122
6.2.1 Context....122
6.2.2 Phase transitions....125
6.2.3 Transcription....127
6.2.4 Analysis and discussion....127

7. Synthesis of results and discussion....134
7.1 Talk and affordances of semiotic resources....136
7.2 Barriers and productive resources....141
7.3 Coherent framing across contexts....144
7.4 Research questions....146
7.4.1 RQ1: Affordances of semiotic resources of IR camera related to resources and framing....146
7.4.2 RQ2 & RQ3: Epistemological and conceptual framing....147
7.4.3 RQ4: Barriers and productive resources....153

8. Contributions and implications....155
8.1 Theoretical contributions....155
8.2 Methodological contributions....156
8.3 Teaching and learning....157

9. Future research....159

Acknowledgements....160

References....161

Appendix A......177
Appendix B......179
Appendix C......181
Appendix D......182
Appendix E......183

Preface

About the author of this thesis

I have been a part of the academic community, as a student in chemistry, mathematics, social sciences and teaching, for almost 12 years. This could either be interpreted as a failure or as proof of my interest in education and learning. I hope that my completed degrees point to the latter. My journey started at the Ångström laboratory in 2008 at Tekniskt basår (foundational year in natural science) where I, among others, was taught by Johan Larsson in physics. I have always had a great interest in both natural and political science and my path at the university mirrors this interest as I, in 2009, went on to study peace and conflict research for almost three semesters before I realized that it was in education, where I could engage in both political science (in the discussions on teacher education and the Swedish education system) and natural science (as school subjects for an upper-secondary school teacher degree). A lot has happened since I made that choice: I was active at one of Uppsala's student nations, Värmland's nation, for 6 years as a librarian, assisting club master, bartender and archivist, at Kuratorskonventet as a chairman for Stipendiekonventet (the scholarship board of Uppsala), at Utrikespolitiska föreningen (the society of foreign affairs) as a journalist at their journal Uttryck, at Uppsala Studentkår as one of the members of the education committee of Lära and one of the founders and for years representative for issues on science teacher education, of the science teacher section, LärNat, at Uppsala Teknolog- och Naturvetarkår (Uppsala Union of Engineering and Science Students). All of these commitments have shaped who I am today but they also mirror my interests and identity (much like how it is mirrored in the research I do).

General notes for the reader

I will at times refer to "I" or "my research" when writing about Paper I and II. However, the work of Paper I and II was a collaborative effort of all the involved authors. My contributions to each paper are expressed in the List of peer-reviewed papers. The thesis, including the added analysis for each separate paper (chapter 7) and the synthesis, are results of my own individual effort though.

Notes specifically for teachers

Education research can often seem to be quite heavy on the theoretical side and teachers usually lack the time to filter through the content that may have a significant value to peers in education research, but that may not be as easy to just apply in a classroom setting. I recommend reading the answers to the research questions, and the chapter on implications for some recommendations on how to apply my results to a teaching context.

Glossary

Affordance – the affordance of a semiotic resource is the main function that the semiotic resource has in conveying some meaning for a specific situation. Affordances are made visible in how participants act and talk in a situation.

Anchoring situations/examples – examples and situations in which intuition is aligned with accepted theory (Clement, 1993) (situated in the teaching, e.g. the teaching target).

Barrier – A resource that inhibits some productive resource or leads reasoning away from a productive reasoning path.

Boundary objects – Scientific objects that are shared among several disciplines and "satisfy the informational requirements of each of them" (Star & Griesemer, 1989, p. 393).

[Conceptual] framing – a coherent activation of some resources that is used to interpret a situation in a way that answers the question "What is this about?" (Hammer, Elby, Scherr, & Redish, 2004; E. Redish, 2014).

Disciplinary affordance – "the agreed meaning making functions that a semiotic resource fulfils for a particular disciplinary community" (Airey, 2015, p. 18).

Deliquescence – the process of a material (often salts) absorbing water from their surroundings (the moisture) until they dissolve in the water.

Ecological huddle – physical organization of a shared point of attention (both cognitive and visual attention), e.g. directing bodies toward something that the talk is about (Goffman, 1964).

Epistemology – assumptions regarding how we can know about the nature of reality.

Epistemological framing – the interpretation of what to do in a situation in order to gain knowledge about the reality.

Exemplar – illustrative event or instance. The individual members of a category. (Nosofsky & Zaki, 2002)

Hygroscopy – a phenomenon involving a substance (hygroscopic) absorbing or adsorbing moisture from the surrounding.

Infrared (IR)/Thermal camera – Camera that detects infrared light which is used to generate a thermal image of whatever it is aimed at.

Instant inquiry – when "acting immediately upon "what-if" questions driven by [..] genuine curiosity" (Haglund, Jeppsson, Hedberg, & Schönborn, 2015).

In vivo/in vitro – in vivo are investigations of cognition in naturalistic settings, whereas in vitro involves conducting controlled experiments on cognitive phenomena (Dunbar & Blanchette, 2001).

Naturalistic settings – the setting which the studied participants practice within in the role that is the target for the study (e.g. the learning of physics students during lab work in a mechanics course is studied in the lab where the physics students are taught the mechanics).

Pedagogical affordance – "aptness of a semiotic resource for the teaching and learning of some particular educational content" (Airey, 2015, p. 18).

Phenomenological primitive (p-prim) – Self-explanatory building blocks of knowledge that act as axioms of intuition (A. A. DiSessa, 1993).

Productive – A resource, framing or reasoning is productive when it leads to predictions, observations and/or explanations that, for the purpose of the teaching context that the learner participate in, is considered correct.

Prototype – a summary representation of multiple members of a category (Nosofsky & Zaki, 2002).

Resource – tools and ways of knowing (E. Redish, 2014), in a cognitive sense, for example exemplars, p-prims and prototypes.

Semiotic system – a category or mode of communication, e.g. colors or form (the shapes of things).

Semiotic resource – a specific member of a semiotic system, e.g. red or blue (system: color), or smartphone-shape (system: form).

Teaching target – the goal of a teaching sequence or teaching situation, e.g. learning more about heat or relating phase transitions with energy transfer.

Thermodynamics – a field, shared by multiple disciplines in science, that concerns energy, energy transfer and transformations and the relationship between for example heat, work, temperature and entropy.

Abbreviations

AAPT – American Association of Physics Teachers
CA – Conversation analysis
CER – Chemistry Education Research
ESERA – European Science Education Research Association
FFPER – Foundations and Frontiers in Physics Education Research
GIREP – Groupe International de Recherche sur l'Enseignement de la Physique
GRC – Gordon Research Conference
ICPE – International Commission on Physics
IPLS – Introduction to Physics for Life Science
IR – Infrared
ISLE – Investigative Science Learning Environment
MBL – Microcomputer-based labs
NGSS – Next Generation Science Standards
PER – Physics Education Research
PERC – Physics Education Research Conference
POE – Predict-Observe-Explain
RQ – Research Question
UNESCO - United Nations Educational, Scientific and Cultural Organization

1. Introduction

1.1 Thermodynamics and education

How to use the word *heat* is a debated topic in *Physics Education Research (PER)*: should it be taught as a process or as a substance (or should teaching about heat be avoided entirely in early education)? Talking about heat as a substance may be easier to relate to in an everyday sense ("do not let the heat out" or "you are freezing, you are losing a lot of heat") but may result in difficulties when trying to understand it as a process of energy transfer, for example in learning about the difference between an adiabatic and isothermal process. It is even argued that heat as a noun encourages "sloppy thinking" (Romer, 2001) and that it misleads students into thinking that heat is a state function (D. Brookes, Horton, Heuvelen, & Etkina, 2005). Others argue that there is a usefulness in the substance metaphor as it leverages intuitive ideas (as long as one is explicit with that it is a metaphor) (Scherr, Close, McKagan, & Vokos, 2012; Wittmann, Alvarado, & Millay, 2017).

Other topics related to the concept of heat are climate change and global warming. The topics have gained a lot of attention during the last couple of years, especially as youth movements, such as Fridays for Future, or Skolstrejk för klimatet (the Swedish name for the movement), have managed to get their message through by going on strike from school until politicians begin prioritizing the topics. But what science knowledge is necessary in understanding what climate change and global warming is all about? A lot could be added to the response to this question but the most basic knowledge that is required to discuss the topics is that of energy analysis, which includes knowledge about *energy conservation* and *energy degradation*. Some researchers (e.g. Dewaters & Powers, 2011) have chosen to talk about *energy literacy* as a way of emphasizing the importance of content knowledge, related to energy, and the implications in action of that knowledge for a general public.

Everything around us can be thought of from an energy perspective in how the *laws of thermodynamics* describe our world:

A thermometer, for example, measures the *temperature* of itself; as energy is transferred between the thermometer and the surroundings it will eventually reach a *thermal equilibrium* with whatever we want to measure the temperature of and thus we are able make conclusions about the temperature of the environment. Another way of describing this is through the *zeroth law of thermodynamics*: If two systems are in thermal equilibrium with a third system, then those two systems are also in thermal equilibrium with each other. However, the transmission of energy through *heat transfer* depends on the material involved in the systems. This is experienced every time you bake a pizza in your oven: You do not burn your hand every time you briefly put it in the oven to take the pizza out from it, even though the temperature of the oven may be 200 ^{0}C. This is thanks to the poor *thermal conductivity* of the gas in the oven. You do however need to be careful with the metallic oven tray, as metals are good conductors, so you probably use a material that is a poor conductor to protect your hands from the metal, such as some cloth with felted polyester sewn into it (potholders).

The rate of cooling is described through *Newton's law of cooling*: the rate of change of temperature (*dT/dt*) for a body is proportional to the difference between the temperature of the body and its surroundings (T_{body} - T_{surr}). So a cup of coffee at 97 ^{0}C will have decreased more in temperature than a cup of coffee at 70 ^{0}C for a given time interval but this does not mean that it will "catch up" in temperature as the cooling follows an exponential curve.

When taking your bike across a bridge during a cold night in Sweden you may notice that the surface of the bridge tends to be more icy than the road that led to the bridge. This relates to surfaces' relation to the ground under it. While a bridge usually hangs in the air above a stream of water, the road is heated through the ground beneath it.

In arguments against sustainable development you can hear that it does not really matter if we use fossil fuel to drive our cars as energy always is conserved according to the *first law of thermodynamics*. However, adding the *second law of thermodynamics* to the reasoning one finds that, although energy can not be destroyed, it can degrade thus becoming less useful.

Many everyday sensations are the results of nearly or completely invisible thermal processes:

- It stings from the steam condensating on our skin (releasing *latent heat*) when we pour water on the rocks in a sauna.
- When stepping out from the shower stall from a humid environment to a dry environment, water begins *evaporating* from our body requiring energy which in turn makes us feel cold.
- The climate encountered when going outdoors in Europe, which is warmer than what could have been expected at this latitude. is an effect of the high *specific heat capacity* of water as the Gulf Stream carries warm water to Europe thus heating the air that moves across Europe.

There are ways of visualizing these thermal processes, for example through simulations, or through devices generating thermal images, e.g. *infrared (IR) cameras* (sometimes also reffered to as *thermal cameras*). IR cameras are tools that can generate colorful images (see *Figure 1*) based on the infrared radiation detected by the device. Research on if and how IR cameras can be used in education involving thermal phenomena indicate that they invite to *instant inquiry* (e.g. Haglund, Jeppsson, Hedberg, & Schönborn, 2015). My research build on the body of research investigating the potential role of IR cameras in laboratory education by exploring what they bring in terms of *framing* and affordances of *semiotic resources*.

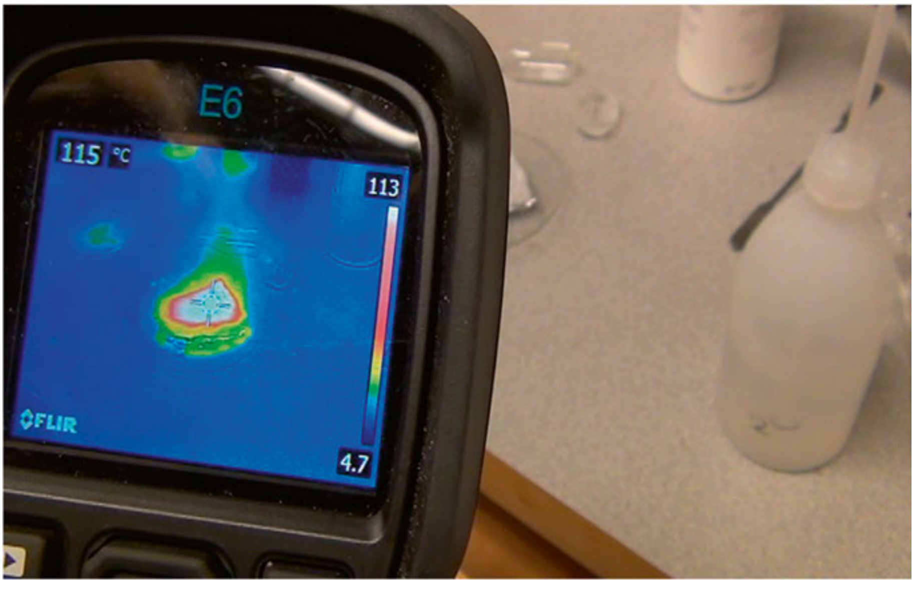

Figure 1. IR camera generating a thermal image of some sodium hydroxide reacting with water on a piece of aluminum foil.

Turning to the research informed by thermodynamics, it is more difficult to try to find some research in physics which does not relate to thermodynamics or energy. Some research does however more explicitly contribute to the field of thermodynamics: for example, research in physics and engineering on *caloric effects* on solid materials for refrigeration, which may lead to more environmentally friendly heat pumps (e.g. Aprea, Greco, Maiorino, & Masselii, 2017; Crossley et al., 2019; Fähler et al., 2012) or the study (Agrawal, Shimizu, Drahushuk, Kilcoyne, & Strano, 2016) of *phase transitions* of water inside of carbon nanotubes which may lead to applications such as ice-filled wires as the *freezing point* of water seems to increase to above 100 ^{0}C when confined in nanotubes.

1.2 The scope of the knowledge claims

In this thesis, I:

- Relate the Resources framework to the framework of Social semiotics: Resources and framing are related to the concepts of semiotic systems/resources and affordances.
- Contribute to the Resources framework: Adding to the already existing box of theoretical tools, I present the concept of barriers as resources that hinder or distract reasoning that may lead towards the teaching target, e.g. productive reasoning. In addition, some productive resources that can resolve the barriers are also identified.
- Elaborate on the concept of framing: I distinguish between conceptual and epistemological framing and look at the potential in having contexts of situations and experiments in a proximity that promotes a conceptual framing that is applied coherently across multiple contexts in a teaching sequence. In addition, the epistemological framing is related to the teaching target through two types of epistemological framing (the inquiry and instructed types) that can be structured or unstructured.
- Analyze the semiotic resources and systems of the IR camera in terms of affordances and how they affect conceptual and epistemological framing.

1.3 Structure of the thesis

Chapter 2 outlines the theoretical frameworks and constructs that relate to the field of PER and, to some extent, more general education research. I present more than the constructs and frameworks I use in my research in this chapter to give a fuller picture of the fields of PER and education research. Much of the content of this chapter is used in the subsequent literature review which is the reason for the introducing theory before the literature review.

Chapter 3 gives a brief introduction of PER to then delves into the research done on thermodynamics and learning, with a focus on concepts such as heat transfer, energy and temperature. The literature review begins with a more general overview of research on thermodynamics education and is then organized according to patterns found during the review that relate to my two papers included in this thesis: Contexts, resources and barriers. This is followed by a review of literature on dynamic visualizations, with a focus on IR cameras in education and the chapter ends with the role of my own research, in the body of literature that has been reviewed, and the research questions of the thesis.

Chapter 4 summarizes the bits of chapter 2 and 3 that form the set of axioms or assumptions for my research.

Chapter 5 deals with the methods for probing for knowledge, analysis and data collection in addition to the paradigm framing these methods. The equivalent to validity and reliability of quantitative research, trustworthiness, is also dealt with in this chapter, which concludes with ethicsal considerations of my studies.

Chapter 6 and 7 include the analyses of Paper I and II with some added analysis and discussion to relate the two papers to each other.

Chapter 7 is the core of the thesis in that it synthesizes the two papers into a discussion that is used to answer the research questions of the thesis. This chapter includes additional analysis of the two studies to further tie them together.

Chapter 8 looks at the extensions of my research in terms of the implications it has on theory, methodology and practice (teaching).

The thesis ends with a chapter (chapter 9) on the future research that will be added to the final doctoral thesis.

2. Theoretical framework

2.1 The learning perspectives

What does it mean to know something? You may get a variety of responses, to a so seemingly simple question, depending on what *epistemology* responders base their reasoning on. There are numerous ways of representing knowledge and defining "learning". A learning perspective can essentially be viewed as a set of axioms or assumptions that forms the basis of one's potential knowledge claims in education research. I will here briefly present some of the perspectives that I have picked my set of axioms from:

Constructivism is a perspective of learning that is based on the assumption that learners build on their previous experience when learning. As this perspective can encompass many different views, Knight (2004, p. 42) coined the term *scientific constructivism* in a way of capturing the "teaching philosophy in which students actively build their knowledge and concepts by constantly testing them against the harsh judge of physical reality". The assumption I bring from this learning perspective is that learning is based on prior knowledge and experience.

This view does not exclude the epistemology of *cognitive science,* or *cognitivism,* in which a common way of modeling how we organize or represent our knowledge in cognitive science is through *nodes* and *connections*, more commonly known as *connectionism* (Gärdenfors, 2004). Cognitive science is also about experience but as memories and cognitive units that represent the links between some knowledge structures at a certain level (ideas, principles, concepts, schemas, etc.). This learning perspective assumes that one can gain knowledge about others' cognitive structures, e.g. what happens in their minds. This is an assumption I bring from this learning theory.

A third important learning perspective is the *sociocultural perspective* which revolves around mediation throughtools such as language in learning. According to Vygotsky (1978), when adding speech and the use of signs to an action, the action changes or transforms into something else than if it would not have been coordinated with speech and sign-making. Acting and speaking are two sides of the same coin, or psychological function, in this perspective: when struggling with a task, speech, even though the learner[1] may not have

[1] Referred to as the child in Vygotsky's Mind in Society (1978).

someone to talk to (so-called *egocentric speech*), is used to coordinate the actions. Hindering such speech may even lead to hindering the accomplishment of the task. When the learner does not find a solution on her own, she may turn to a peer or a teacher and communicate through *socialized speech* which is then internalized. That is, the talk going on between learners tells us something about the learning on both a social and cognitive level. This is the assumption that I bring with me from this learning perspective: talk, or speech, can be used to analyze the mind in terms of learning, or rather, *meaning-making*.

Whenever I use *learning* in the thesis, I refer to the *meaning-making* towards some *target of teaching*, i.e. that the content makes sense for the learners in addition to that it is relevant for the teaching unit that they participate in.

2.2 Knowledge as pieces or resources

Learning perspectives, or learning theories, that assume that it is possible and worthwhile to study how our mind works when learning, that is cognition, seem to have the notion of some kind of primary units or constructs of knowledge in common. In the paper *Toward an epistemology of physics* (1993), diSessa proposes that we have a type of building blocks of knowledge that have the same function as physical laws in that they are self-explanatory, i.e. they are explained by “That is just how it is”. He calls these constructs *phenomenological primitives* (*p-prims*).

Experiences early in life could form these primitives. For example when we are able to push and pull objects, we learn that it is common that larger objects require more push or more pull to be moved or that different surfaces affect the effort required to push an object (*Ohm’s p-prim* as described by diSessa (1993)). The satisfaction in exploring new effects of our actions drives the foundation of new primitives. This drive was suggested as the fundament of learning already by Thorndike in 1923 in his book *Education: A first book* (1923, p. 78), where he calls this the instinct of “Pleasure at being a cause”.

P-prims may be self-explanatory and have the function of *axioms of our intuition*. The aim of education is to help learners to activate a p-prim in the appropriate circumstance, thus supporting the activation of other cognitive elements for the context specified by the p-prims. These p-prims are then the intuitive knowledge that an expert, in diSessa’s sense, would know how and when to use. Conceptual development of learners is through this perspective partly a result of the mechanism of shifting contexts (A. A. DiSessa, 2014). That is, to learn in what contexts to apply a certain composition of resources for it to be *productive*, i.e. useful in coming to a, for the teaching situation, correct answer. A context in this case would “heuristically refer to an ambient, although subthreshold, external activation (in most cases of relatively long-term duration), which functionally prepares an element to fire on the basis of some critical set of activation links" (A. A. DiSessa, 1993, p. 180). For example (E. Redish, 2004), a student in physics may apply the p-prim *"closer is stronger"* to the question why the temperature changes with the different seasons of the year. This would result in the response "Because the distance between Earth and the sun changes over the year", perhaps as a result of activation of the p-prim through the context "seasons vary with Earth's movement in relation to the sun", which may then be considered as a *misconception* by many educators. However, the underlying p-prim is correct for some *contexts* and *phenomena*, the learner just needs to learn when to apply the p-prim and when not to do it (it really does become "hotter" the closer you get to a fire).

The idea of fine-grained, flexible cognitive, or epistemological units is also the core of the *Resources framework* (E. Redish, 2014) in which the units are referred to as *resources*[2]. The fundament of the Resources framework has been developed over many years by for example Clement, Brown & Zietsman (1989), diSessa (1993), Hammer (2000) and Redish (2004), and was proposed as a way of theorizing PER which has historically often attended to observations and practice but more rarely to the mechanisms of the science, that is, the theory of the teaching and learning of physics (E. Redish, 2014).

The Resources framework acknowledges both cognitive and sociocultural structures of knowledge but contextualizes the usefulness of the "grain-size" of what is being analyzed through the framework: Psychological models and behavioral phenomenology can be used to analyze the knowledge of the individual, but if one wants a less fine-grained analysis, for example by analyzing groups of students engaging in discussions, then ideas from Vygotskyan theory (e.g. Vygotsky, 1978) may be of more use than a model of our memory system. Redish (2014) refers to this metaphor of levels of knowledge as *the grain-size staircase*: The knowledge that students bring from each of the levels in the staircase affect what they make of a situation that they encounter, in other words, the "student's perception of the sociocultural environment […] affects that student's behavior" (E. Redish, 2014, p. 543).

The Resources frameworks borrows the term *framing* from anthropology (Goffman, 1986) to describe students' interpretation what a situation is about (E. Redish, 2014). Hammer et al. (2004, p. 9) write that "To frame an event, utterance, or situation in a particular way is to interpret it in terms of structures

[2] The resource is a cognitive construct. A physical object can not be a resource in its own right. A resource is first employed when a person interprets the object through association. For example, when a student says that a salt is "melting", she may employ a resource associated to melting; the prototype of a melting solid (perhaps close to melting ice as that is a common phase transition of the sort) through the similarities of the situation of the prototype and the observed situation. This allows the student to apply whatever she associates with the prototype to the observed situation, for example that the ice melts when it is brought out from the darkness of a freezer into a light room thus leading to the hypothesis that light causes the salt to melt, etc.

of expectations based on similar events". So, based on some structures in the environment, one interprets a situation based on experienced situations that share some similarities with the encountered situation (Hammer et al., 2004). This could be some visual aspects in the environment that one attends to, or spatial dimensions of the room in which the situation takes place: A student asked a question during a tutorial may not respond with the same anxiety as when getting the same question on an exam in an examination hall as the student does not frame the first situation as an assessment situation, as the stakes are not as high as in the second situation (perhaps partly determined by the type of room they are asked the question in, among other aspects). Another example: most people would probably dare to walk across a plank lying on the floor but the same people would probably not dare to do it if asked to walk across the same plank at a height of 100 m. The plank and task is the same but the context has changed and so people frame the task differently (it is now a task where you risk your life).

Other research applying the construct of framing (Haglund, Jeppsson, Hedberg, et al., 2015; Sande, Greeno, & Greeno, 2012) have added layers to the concept by splitting it into multiple types of framing: Sande, Greeno & Greeno (2012) use *positional, epistemological* and *conceptual framing* to describe how participants frame themselves and each other (e.g. the roles), the interpretation of what type of knowledge that is relevant for a certain activity (both to bring into the situation, and to construct, in succeeding with the activity), and the ways to organize the knowledge in the situation or activity (the relations between the pieces of knowledge and information attended to and not attended to in the situation). Haglund et al. (2015, p. 6) choose instead to use epistemological framing to describe "what kind of knowledge is seen to be relevant in a certain situation" and conceptual framing for "what knowledge is relevant". I will, in this thesis, use conceptual framing as used by Haglund et al. (2015) , e.g. the interpretation of the situation in deciding what the situation is about in terms of what knowledge, or resources, are important for the situation. Epistemological framing will, however, be used to describe how one interprets a situation in terms of what to do in the situation (how to talk, how to act, etc.), e.g. what the relevant practice or behavior is for the situation. The decision in changing the way epistemological framing is used is based on how an epistemology is defined: An epistemology is the answers to the question "How do we know about reality?" (in contrast to an ontology which is the views about the nature of reality) (Coe, 2012). Thus the epistemology is enacted through the actions and the talk used in an activity, e.g. the ways and practice one decides to use in learning about reality.

So, *contexts* allow for certain *cues* which are noticed by the learner who then activates some *cognitive resources* as she *frames* a situation in a certain way. There are fine-grained resources that may be scientifically correct for some contexts but not for others and that act as "mini-generalizations from experience whose activation depends sensitively on context" (Hammer et al., 2004, p. 6). How these resources are activated depends on the context in terms of the framing (Hammer et al., 2004) of the situation. An object in the environment may be associated to some resource or resources which affect the conceptual framing that is applied to the situation. This may determine what aspects that the individual attends to and what other resources are activated.

Students' framing of situations is thus a potential explanation of the varied responses given to the same question in different contexts (e.g. Neumann et al., 2013; Stewart, Griffin, & Stewart, 2007). For example, in *Figure 2*, an individual encounters a situation which is framed as a some kind of science experiment as the individual notices the scientific equipment on the table that contextualizes the situation: The individual applies one or multiple cognitive resources, associated to the tool, to try to explain what is happening (to frame it) and come to the conclusion that someone is doing an analysis of the liquid in the beaker with the microscope.

2.3 Other resources

Other cognitive units of knowledge that I include under the concept of resource include *exemplars* and *prototypes* (e.g. Smith, 2014). In this case, exemplars refer to individuated memory representations for a category or class of objects. For example, an exemplar of a tree could be the most previously experienced tree. Given enough experience of some objects or events, e.g. a wide variety of exemplars, we are able to form abstractions, of the classes or categories, called prototypes.

Prototype is a concept introduced by Rosch (1973) which originally described the objects of a certain category that represents the category, for example "robin" is the prototype of the category "bird" (it is more prototypical than a penguin, a frozen chicken or rubber duck).

Figure 2. An individual is trying to make sense of a situation through framing and applying cognitive resources depending on the contextual factors noticed.

These concepts will only play a small part in this thesis as I will mostly refer to resources when I talk about either exemplars or prototypes (the concept of *productive resources* will be contrasted with the concept of *barriers* at a later point in the thesis). However, the concepts do tie in to the future research that this licentiate thesis will lead up to: a more fine-grained analysis of the resources used in reasoning processes on phase transitions (C. R. Samuelsson, Haglund, & Elmgren, 2019).

2.4 Knowledge as meaning

A non-dualistic way of interpreting *Figure 2* is offered by the theory of *gestalt psychology*, from which Gibson (1979) introduced the concept of an object's *affordance*: "[…] what the objects affords us is what we normally pay attention to" (Gibson, 1979, p. 134). The affordance "[…] points both ways, to the environment and to the observer" (Gibson, 1979, p. 129) and is thus non-dualistic. Gibson (1979) adds that, although the affordance is always there to be perceived by someone, whether one attends to, or perceives, the affordance depends on the needs of the individual.

Through this interpretation, the environment in *Figure 2* affords some kind of physical analysis and optical enlargement (affordance of the microscope), but the beaker also affords drinking, and the microscope affords keeping papers in place (as a paperweight).

An alternative take on the concept of affordance was given by Norman (1988) who referred to the possible actions perceived by an individual as the *affordance* of something. Affordance in Norman's (1988) definition is not invariant as in Gibson's (1979) definition, but varies with the capabilities of the agent as a sort of likelihood of use. For example, for an individual who has never encountered a microscope before, the affordance of the microscope in *Figure 2* may still be that of enlargement (as the person may relate the form of it to binoculars) but perhaps not physical analysis (as its designed purpose is unknown to the person and thus not perceived as such). Norman (2013) did however update his definition, in a later publication, to "An affordance is a relationship between the properties of an object and the capabilities of the agent that determine just how the object could possibly be used. […] Affordances determine what actions are possible" (Norman, 2013, pp. 11, 14). In this way, for most people, an affordance of a thermometer would be measurement (of temperature).

I use the concept of affordance with a slightly more context dependent definition: the affordance of a semiotic resource (see below for description of this construct) is the main function that the semiotic resource has in conveying some meaning for a specific situation. Affordances are made visible in how participants act and talk in a situation. The affordance of the semiotic resource may change with the context, e.g. the color red and the form of a heart may afford a sense of love when used on a Valentine's day postcard (e.g. the card is conceptually framed as sent with affectionate intent) if the receiver is interested in the sender. If the card has been sent by someone who the receiver despises, the affordance of the color and the form could instead be a sense of mockery or disgust (depending on the relationship between the sender and the receiver).

It should therefore be important for researchers to investigate "human beings in relation to specific contexts, rather than abstract tasks" (Dunbar & Blanchette, 2001, p. 335) as the context reveals the affordances of an object, or semiotic resources.

The theoretical contributions of Norman and Gibson are however very general as they describe affordances of objects to interacting *agents* (Norman, 2013), or environments to *organisms* (Gibson, 1979). In PER, researchers investigate the teaching and learning of *physics*, usually in a disciplinary environment with discipline-specific equipment, language, representations and practice. Thus, there is a need for a more specialized theory to acknowledge the way physics is structured and practiced.

A response to this need has been offered by Fredlund, Airey & Linder (2012) in the theoretical construct *disciplinary affordance*: "[…] the inherent potential of [a] representation to provide access to disciplinary knowledge." (Fredlund et al., 2012, p. 658). Disciplinary affordance is based on Gibson's (1979) concept of affordance but takes the meaning potential of discipline-specific representations into account. The term "representation" is in this case wider than the everyday interpretation of the word: Airey & Linder (2009, p. 29) describe representations as "*semiotic resources* that have been designed specifically to convey the ways of knowing science" and relate this to the *multimodality* concept of *modes* (e.g. Jewitt (ed.), 2017).

In the framework offered by Airey & Linder (2009), a system of semiotic resources may be made up of modes such as gestures, apparatus, images, etc. Later development of the framework (Airey & Linder, 2017) has excluded the use of mode to instead describe the ways a particular social group communicate through the concept of semiotic resources. Semiotic resources include language, mathematics, graphs, but also laboratory apparatus, which would not be considered a representation in an everyday sense.

A socially organized set of semiotic resources (e.g. colors, graphs, etc.) is referred to as a *semiotic system* (modes in the original framework of social semiotics (Jewitt, Bezemer, & O'Halloran, 2016). This aligns with the framework of *Social semiotics* (Halliday, 2007) in which a culture is made up of a system of meanings (a social semiotic). The framework offered by Airey & Linder (2009), which also is referred to as Social semiotics, builds on the Social semiotics of Halliday (2007) but is, in contrast to the framework of Halliday (2007) and Gibson (1979), specialized towards the study of understanding teaching and learning in physics. Included in this framework is, in addition to disciplinary affordance[3], which, through the terminology of Social semiotics, is defined as "the agreed meaning making functions that a semiotic resource fulfils for a particular disciplinary community" (Airey, 2015, p. 18), also the concept of *pedagogical affordance*, or the "aptness of a semiotic resource for the teaching and learning of some particular educational content" (Airey, 2015, p. 18). With these two theoretical constructs, it is possible to study the potential of a tool in supporting the everyday practice for both disciplinary members such as researchers and teachers in a discipline, and the potential in supporting learners in their education on content related to the discipline.

Much of the knowledge in physics is invisible and thus *appresented* (Marton & Booth, 1997). If encountering a situation in which this knowledge is relevant for the learning process it is easily missed as it does not become a part of the learner's framing of the situation. Semiotic resources supporting the accessibility of this knowledge can be said to have pedagogical affordance as it helps the learner to pay attention to the aspects relevant in reasoning about the situation (it *unpacks* the embedded information). However, what is appresented for the novice may not be appresented for the more experienced expert: A person encountering a table for the first time may not be aware of the appresented legs when seeing the table from above. Someone who has

[3] The reader may have noted that disciplinary affordance is defined twice. The early definition of Fredlund, Airey & Linder (2012) and the later updated definition by Airey (2015). I use the later definition in this thesis (see the glossary) as the affordance is not inherent in the object in that definition but rather situated in the disciplinary community of users.

experienced many tables before know that it typically include legs that lift the top of the table from the ground, that is they are aware of what is appresented, but can not be completely sure until they have tested their prediction, by for example bending down to observe the potential legs of the table.

It has been suggested (Airey, 2015) that there is an inverse relationship between pedagogical and disciplinary affordance: the decrease of one leads to the increase of the other, for example by altering a circuit diagram by adding colored dots to indicate appresented aspects of the representation, Fredlund et al. (2014) showed how the affordance of the diagram may be shifted from disciplinary towards pedagogical affordance. The shift adds semiotic resources that may be considered extraneous for someone with more experience of the discipline but supporting for a learner.

Returning to *Figure 2*, a Social semiotic starting point in explaining the situation when the individual encounters the table with equipment could be that of the semiotic resources of the equipment on the table: For example the form (semiotic resource) of the microscope that affords enlargement (long tube with lenses on both sides resembling a binocular) or the color (semiotic resource) of the liquid analyzed through the microscope. The form resembling binoculars gives the microscope a pedagogical affordance in that the disciplinary meaning of the tool is unpacked through its resemblance to an everyday tool. The color of the liquid could however have a high disciplinary affordance: A researcher in the discipline would be able to discern its meaning and use experience in determining its properties by recognizing the liquid from its color. In addition, it could have a low pedagogical affordance: Someone from outside the discipline could have difficulties in explaining what it is and may associate the color to something that is irrelevant for the situation.

2.5 Making meaning through talk and interaction

"[…] conceptual knowledge is the substance of our intellectual repertoire that is used to communicate thoughts and ideas to others" (Erickson, 1979, p. 221).

As the assumptions of what knowledge is in this thesis have been outlined in the previous sections, it is now time to turn the attention towards how that knowledge is negotiated and synthesized through the interactions and communication with other individuals such as peers or instructors.

Building on the epistemology of *social constructionism*, Lemke (1990) outlines the basis for his version of Social semiotics in his book *Talking science: Language, learning and values*. In my thesis, two of these aspects, namely language and learning, form a basis for the theoretical perspective on interaction in laboratory practice: how students (and the instructor) talk with each other tells us something about how they learn or where they are in their learning process. This adds on the third assumption from 2.1 The learning perspectives, that the talk of learners says something about their minds in terms of learning.

Building on the Social semiotics of Halliday (2007) and classical *Semiotics* (Eco, 1979; Peirce, 1931), Lemke (1990) proposes his Social semiotics, on how people make meaning. As mentioned earlier, this theory has later been adapted for PER (Airey & Linder, 2017) but I would now like to elaborate a bit on Lemke's Social semiotics as it includes two theoretical constructs of communication, *thematic patterns* and *organizational pattern* or *activity structure* (Jay L Lemke, 1990) that relate to a *typology of talk* (Mercer, 1995) which I use in my research. On activity structure, Lemke (1990, p. 19) writes that "All social cooperation is based on participants sharing a common sense of the structure of the activity: of what's happening, what the options are for what comes next, and who is supposed to do what". In other words, the activity structure sets the expectations for how a dialogue is supposed to unfold. While engaged in a science dialogue, participants relate concepts and symbols to each other to form complex meanings for example when making statements like "heat spreads out" together with "temperature becomes the same everywhere" may indicate an initial understanding of *thermal equilibrium*. This type of organization of *semantic structures* through talk is, by Lemke (1990), referred to as thematic patterns.

Learning science for Lemke (1990) means learning to talk science. Lemke (1990, p. 157) goes as far as to even doubt the effectiveness of laboratory work in teaching, if the students do not know how to communicate within that setting: "[...] students do not seem to have enough command of the language they need to be able to figure out what is really going on in the lab while it is happening". However, applying a Social semiotic framework where learning is meaning making, learners may develop a language (and other semiotic resources) to describe and explain the phenomena they encounter in a lab while carrying out the lab (D. T. Brookes & Etkina, 2015). In this sense, the learner does not have to have a language to handle the encounters in the lab before the lab for it to be "effective", the language is developed while doing the lab. Brookes & Etkina (2015, p. 776) argue that the technical terms, or language, should be introduced only after the learners have established "an agreed meaning in the classroom learning community" and that "[…] phenomena are described and explained in strictly non-technical terms. Introducing technical terms only happens later when the underlying mechanisms, the how and why of the phenomenon, is familiar to the members of the learning community."

The importance of talk has also been emphasized in studies on learning thermodynamics, like being explicit with readouts (Kluge, 2019), sharing the information that one individual has with the rest of the group through talk, or processing knowledge and testing ideas through discussions (Carlton, 2000; Tobin et al., 2019). Additionally, discussions seem to be important for learners when supported by technology in the processing of new knowledge (e.g. Haglund et al., 2017; Kluge, 2019; Nordine & Wessnigk, 2016).

Mercer (1995) has, similar to Lemke (1990), an emphasis on talk in the study of learning and knowledge. Mercer (1995) does, however, in contrast to Lemke (1990), acknowledge the role of thought in learning but adds that "Knowledge is also a joint possession, because it can very effectively be shared. What one human being discovers [...] can be made available to others" (Mercer, 1995, p. 1). Building on the ideas of Vygotsky (1978), Mercer (1995, p. 4) refers to language as a "social mode of thinking" and thus links thought to language in a similar way as Vygotsky (1978) did: language as a tool to develop one's thought and think together with others. In multimodal analysis (Jewitt (ed.), 2017), semiotic systems such as gestures and images are important means of communication that need to be considered by a researcher when doing an analysis. However, Mercer (2013) acknowledges the importance of systems other than language in learning processes but cautions researchers about obscuring the central role of language by putting too much emphasis on for example non-linguistic symbols or gestures. By analyzing the talk of students in primary school, Mercer (1995) found three types of talk that represent distinctive social modes of thinking that can be used to relate how talk is used in sharing knowledge by thinking together. The three types of talk are:

- *Disputational talk* – characterized by individual choices and assertions. Characteristics include disagreement and individual decision-making. Participants in the talk usually disagree but do not accept any alternative hypotheses offered by others.

- *Cumulative talk* – a positive construction of knowledge. Positive in that the talk lack any criticism or alternatives. Knowledge is accumulated through repetitions, elaborations and confirmations (the characteristics of the talk).

- *Exploratory talk* – challenges are made but justified, alternative hypotheses and suggestions are offered for the participants to jointly consider. Characterized by challenges and multiple explanations or hypothesis offered for joint consideration.

There is a personal investment in the arguments of disputational talk that may lead to participants being fixated by an individual decision that they have made. In exploratory talk on the other hand, the "knowledge is made more publicly accountable and reasoning is more visible in the talk" (Mercer, 1995, p. 104). The typology has been employed in PER by Andersson & Enghag (2017) in a study that explores how communicative moves relate to outcomes of actions in a physics lab. They found that, regarding the physics content of the work, cumulative talk expressed students' purpose of completing the task at hand and handling equipment, the disputational talk expressed the purpose of reinforcing some previous knowledge and exploratory talk expressed conceptual understanding, creation of new knowledge and the synthesis of each other's ideas. Andersson & Enghag (2017) include an analysis of the talk on a linguistic level, which includes discursive moves that fit with the characteristics that Mercer (1995) suggests for the three types of talk (counter assertions for disputational talk, confirmations and repetitions for cumulative talk and challenges, acceptance and extensions for exploratory talk).

In Social semiotics, where learning is considered as meaning-making, actions such as gesturing and building are also part of the learning process (Jay L Lemke, 1990). One could say that these are different semiotic systems (or semiotic resource systems in Lemke's (1990) terminology) which can be coordinated together with a semiotic system such as speech in the activity of talking and discussing. When using a specific type or subset of a semiotic system, for example red and blue from the semiotic system of colors, these specific members of the semiotic system may be referred to as semiotic resources (more commonly referred to as representations in PER (Airey & Linder, 2017). Semiotic resources may form a coordinating hub (Fredlund et al., 2012; Volkwyn, Airey, Gregorcic, Heijkensköld, & Linder, 2017), a hub in a learning sequence around which meaning can be negotiated between students. For example, Volkwyn et al. (2019) found that students attempting to find the direction of Earth's magnetic field with a MBL (IOLab) used paper arrows as placeholders for the negotiated meaning. As physical arrows, they acted as persistent semiotic resources or coordinating hubs that other, non-persistent semiotic resources can be coordinated around, for further meaning making. The persistence of a representation seems to be important for the learning process but Euler, Rådahl & Gregorcic (2019) suggest that non-persistent representations also could form coordinating hubs as if they were semi-persistent, for example the embodied image of a dance acting as a hub for exploring periods of binary stars.

The idea of the body as central to learning can be said to be based on the assumption that learning is to experience: If we base our learning on what we have experienced, education researchers should really find what we have experienced the most of as that experience will act as the looking glass which we observe and understand the world through. Since we were born and until we die, we experience our bodies more than other physical objects that we may encounter throughout our life, as we always carry it with us and act through it in all kinds of different contexts. As such, it is not only the most common experience we have but also the experience that we have tested and transferred between most contexts. Returning to the initial assumption, if learning is based on previous experience, then the body is important to consider when studying learning.

The body is important in the organization of talk: For talk to be meaningful[4], the "talkers" or participants in the conversation should attend to the same object of attention. This require the initiator to find a way to make the aspects or object of the talk to be forefronted, for example by pointing at, looking at, or directing the body towards, the aspects that the initator wants the participants to attend to. The established, physical organization of the shared point of attention is what Goffman (1964) refers to as an *ecological huddle*, a focus of both the cognitive and visual attention. A shared point of attention can be established by directing bodies and gaze toward the focus of a talk, thus forming this ecological huddle.

[4] Meaningful for learning rather than for strengthening some social bonds. Small talk (phatic communion), for example may not be engaging or meaningful for learning something (the words used does not matter much for the talk) but it may act as a way of testing and establishing social positions (Laver, 1975). In this study, however, the participants have certain role and know about their social status in the situation, thus talk is rather used for investigating, negotiating and testing some knowledge.

3. Literature review

This literature review is of three parts: a general introduction to the structure of PER as a field of research, a literature review of research done on the learning of thermodynamics and a review of the research on dynamic visualizations in education with a focus on IR cameras. The second part is mainly on learning the content of thermodynamics: what difficulties students encounter in learning thermodynamics, what causes the difficulties and how they can be understood and addressed in teaching. The content specifically brought up in this part of the the literature review, related to thermodynamics, is heat, temperature, energy and phase transitions. The third part is framed by the second part and so mainly reviews research on a dynamic visualization technology, the infrared (IR) camera, that is designed for observations and experiments in thermodynamics.

3.1 PER

Much of the literature review on the American PER is based on Beichner's (2009) paper and a paper by Docktor & Mestre (2014). I have also had help in having discussions with Michael Wittmann and Rachel Scherr, at the Gordon Research Conference 2018, about the most dominant theoretical frameworks used in American PER.

I have turned to other sources than papers for the review of European PER, such as the organizations GIREP (Groupe International de Recherche sur l'Enseignement de la Physique), ESERA (European Science Education Research Association) and the archives of UNESCO (United Nations Educational, Scientific and Cultural Organization). In addition, I have looked at the research of some of the European PER that is referred to in an early resource letter on PER (L. C. McDermott & Redish, 1999) to identify the research that has influenced a lot of European PER done today.

3.1.1 American PER

The American research field of PER is about 45 years old (Docktor & Mestre, 2014) as it could either be said have started when Lillian McDermott was hired at University of Washington and began conducting studies on students' conceptual difficulties in physics (Beichner, 2009), or in 1973 when the first research division in PER was founded (AAPT, 2013). The field grew over the years through the interest it attracted from other physicists that started up new divisions on their own. This includes David Hestenes at Arizona State and Dean Zollman at Kansas State (Beichner, 2009). Some major advances were made beginning in the 1990's and onwards: PERC (Physics Education Research Conference), one of the major conferences in the American PER community was created and in 2000, the Gordon Research Conference started their first specialized PER conference series, GRC on Physics Research & Education. In 2005, another specialized conference series, FFPER (Foundations and Frontiers in Physics Education Research) started.

Researchers in *science education* are more commonly found at departments of education but it is common for researchers in PER to be found at physics departments as research on university physics education often requires a higher knowledge of physics.

However, researchers in PER occasionally collaborate with researchers in science education, sometimes on physics topics (e.g. Ingerman, Linder, & Marshall, 2009) or in developing theoretical frameworks (e.g. Hammer et al., 2004). It is also common for researchers to move between positions in science education research and PER: for example, David Hammer did his PhD in science and math education and is now a professor at a department of physics (Tufts University), Svein Sjøberg did his PhD in physics but is now a professor in science education, etc.

Researchers in science education have also had important roles in the development of PER, for example Paul J. Black, professor in science education who acted as the chairman for the International Commission on Physics Education (ICPE) (Black, 1998). And vice versa, the original boards of ESERA included both Duit and Viennot. Regardless of this movement, the content in focus in PER has traditionaly mainly been the content taught and practiced in the discipline of physics, such as mechanics, thermodynamics and optics and this is why I, in my literature review, have chosen to start out from the physics content of my research: thermodynamics.

More recently, however, the research on energy and thermodynamics education, within PER, has broadened to topics such as the teaching of physics to students in other disciplines or study programs such as life sciences (e.g. D. T. Brookes & Etkina, 2015; Dreyfus, Gouvea, et al., 2014; Geller et al., 2019), teacher education and development (e.g. Daane, Vokos, & Scherr, 2014; J. Larsson, 2019; Wittmann, Alvarado, & Millay, 2017) and students at levels of education other than university, such as middle school and high school education (Neumann et al., 2013; Wittmann et al., 2019). The cohorts included in my papers add to this as I have studied engineering students and instructor in a chemistry course involving thermodynamics, and primary school teacher students in a physics unit of a broader course on science education.

A paper by Docktor & Mestre organizes general PER in six different strands or topics (see *Table 5*). However, the paper by Docktor & Mestre (2014) does not cover the research of some of the major European groups of PER (Fischer, Duit, Viennot, Michelini & Koponen to name a few) and should therefore been read in the light of that fact. The European research of PER is the topic of the next heading.

Docktor & Mestre (2014) identify six topical areas that PER covers:
1) Attitudes and beliefs about teaching and learning
2) Problem solving
3) Cognitive psychology
4) Assessment
5) Conceptual understanding
6) Curriculum and instruction

These areas will be elaborated on, and tied to, the upcoming chapter on learning of thermodynamics, in chapter *3.5 Situating my own research*.

Beichner (2009) has a paper similar to the one published by Docktor & Mestre (2014) on the history and structure of PER (again, American PER as it lacks any information on the European strand of PER). Beichner organizes PER as three types: Basic, applied and other PER. Basic PER covers theoretical research, applied PER covers research on assessment of instructive methods and other PER covers all the research that can not be classified as one of the other two types, but especially the type of research that Docktor & Mestre (2014) refer to as Attitudes and beliefs about teaching and learning, a domain of research in PER.

3.1.2 Three American frameworks

In line with the quantitative tradition of science, early research in PER (e.g. Lawson & McDermott, 1987; Trowbridge & McDermott, 1980) relied largely on quantitative, data-driven methods to investigate students' learning. Although even early studies such as Trowbridge & McDermott's (1981) investigation of students' understanding of acceleration did include qualitative methods such as interviews in their methodology, it became more common when analysis of video interview data was popularized in PER in the late 1990s (Beichner, 2009). As Beichner (2009) puts it, there are benefits and drawbacks of both *qualitative* and *quantitative* methods as one gets generalizable results from quantitative research but with a poor resolution as one usually lacks any information of what happens during the learning process. In contrast, a qualitative method, such as think-aloud protocols, gives the researcher a rich dataset in terms of how the learning process unfolds in real-time but usually a bad generalizability. A more powerful type of methodology is then one in which both types of methods are mixed (*mixed methods*).

However, these types of methods do not have to assume any theory, which is why Redish (2014) describes a science as a three-legged stool on which the legs represent observation, practice and mechanism. He argues that the leg of mechanism or theory has been missing in much of the early PER as it tended to focus on observation and practice in the research process. What we as researchers in PER need, according to Redish (2014, p. 538), is "something that can provide a structure for interpreting observations, for developing and testing models that can grow and accumulate knowledge scientifically, and can guide the creation of appropriate methodologies".

Three frameworks that have been developed based on the premise that prior knowledge and experiences may be productive in a learning process have gained ground in the American PER community: Knowledge in Pieces (A. A. DiSessa, 1993; A. DiSessa & Sherin, 1998), Dual-Processing (Evans, 2008; Heckler, 2011; Daniel Kahneman & Klein, 2009) and The Resources Framework (Hammer, 2000; Hammer et al., 2004; E. Redish, 2004). I employ the third of these frameworks in my research (see chapter *2. Theoretical framework* for a longer description of this).

In the *Knowledge in Pieces* framework, as presented in Chapter 2, Theoretical framework, knowledge is represented as fine-grained structures called phenomenological primitives (p-prims) (A. A. DiSessa, 1993) that may or may not be productive for learning depending on the situation. The learner has to learn what knowledge is relevant and irrelevant for a situation (displacement) and integrate prior knowledge (incorporation) into a coordination class (e.g. A. DiSessa & Sherin, 2014; Kluge, 2019).

In *Dual-Processing*, or *System 1/System 2*, reasoning is made through one of two systems: System 1 which represents the intuitive and automatic type of thinking, or System 2, which represents effortful and careful reasoning (and self-monitoring) (Daniel Kahneman & Klein, 2009). The challenge in solving a non-intuitive problem is then not the prior knowledge itself but rather what type of thinking that is applied to the problem: If a learner is to solve a problem that is non-intuitive, the learner (and expert) need to switch to System 2 type of thinking and carefully reason through the problem.

The *Resources framework* expands on Knowledge in Pieces and some other ideas from PER that highlight the productiveness of prior knowledge. For example the concept of *anchoring* (Clement et al., 1989) which describes prior knowledge of students that align with physics and as such can be used as a sort of *bridging analogies* to use the knowledge in other contexts, or how cognitive resources are linked to culture through how a student frames a situation (Hammer et al., 2004) .

Research in education has over time used different words to describe the ideas that learners start out from. They are sometimes called *misconceptions* or *preconceptions* (Clement, 1987; Hewson & Hewson, 1984; Johnstone, MacDonald, & Webb, 1977; Posner, Strike, Hewson, & Gertzog, 1982; Sokoloff, Laws, & Thornton, 2007), however, researchers have argued the need to separate between preconceptions and misconceptions (Clement et al., 1989) as preconceptions may be "correct" in a disciplinary sense. In addition, later research has shown how the productiveness of the preconceptions depends on the context in which they are used (Dreyfus, Sawtelle, Turpen, Gouvea, & Redish, 2014; Wittmann et al., 2019) and that knowledge itself is *dispersed* across contexts (e.g. light as a wave or a particle) (Linder, 1993).

3.1.3 European PER

I will here outline some of the history of the European PER that I find relevant to my research, such as the teaching and learning of thermal phenomena and the energy concept.

In the 1950s, even though the discipline of physics changed quite drastically in the early 20th century, the teaching of physics had not changed content much since the 19th century. As a reaction, projects like the Nuffield Physics project (Fuller & Malvern, 2010; Nuffield Foundation, 2017) were initiated and international seminars on physics education were arranged to encourage the development of physics education up to date with the discipline of physics. The idea was to get students to experience science, not much different from the vision of the more modern, American project, Next Generation Science Standards (Lead States, 2013).

The Nuffield project led to content such as molecular *specific heats*, *conduction* and *kinetic theory,* as a model of molecules in random motion, being introduced in specifically British physics education but also in other European physics education. The project also put a stronger emphasis on lab practice, discussions and active thinking for learning the content. A similar project was developed for chemistry education.

International meetings on physics education were arranged by OECE, now OECD. As the support of OECD came to an end in 1964 it was decided by some of the former participants that the meetings were too important to discontinue and as a result the international organization for the improvement of physics teaching, GIREP (Groupe International de Recherche sur l'Enseignement de la Physique), was founded 1966. The newly elected president of GIREP, W. Knecht, were also editor of the UNESCO publication *New Trends in Physics Teaching* (e.g. Knecht, 1968), a publication reporting on the contemporary community of physics teaching.

3.1.4 Some European frameworks

European research, especially German PER (e.g. Duit, Gropengießer, Kattmann, Komorek, & Parchmann, 2012), has been influenced by the *Didaktik* tradition which goes back to Wolfgang Ratke and Johan Amos Comenius in the early 17th century (Kansanen, 1999). Kansanen (1999) describes the intermediate stages of Didaktik as the theorizing of teaching and learning through the *geisteswissenschaftliche Didaktik* of Wolfgang Klafki. Within this research, Klafki (1958) proposed ways for teachers in analyzing the teaching content from a *Bildung* perspective. Klafki's research is sometimes considered as one of the earliest examples of what is now referred to as *didactical models* (Wickman, Hamza, & Lundergård, 2018). Other models have later been developed through European education research and this tradition is still an important part of European PER, for example, see the *Systems-Transfer model* proposed by the German researchers in PER (e.g. Duit & Neumann, 2014; Kubsch, Nordine, Neumann, Fortus, & Krajcik, 2019; Nordine et al., 2019).

Other examples of didactical models, although not developed within PER that are used in PER, is *Variation theory* as part of *Learning study* (Marton, 2003) which is used as a theoretical lens in Swedish PER (Eriksson, 2014; Fredlund, Airey, & Linder, 2015). In addition to the mentioned models, Wickman, Hamza & Lundegård (2018) refer to the *Multimodality framework*, developed by, among others, Kress and van Leeuwen (e.g. Jewitt (ed.), 2017) as a didactical model. Regardless of whether it is to be considered as such, it is a perspective that is used in Swedish PER, through the theoretical framework of Social semiotics (e.g. Dolo et al., 2018; Euler et al., 2019; Tobias Fredlund, 2015; Volkwyn, Airey, Gregorcic, & Heijkenskjöld, 2019) as developed by Airey & Linder (2017).

3.1.6 CER & PER

Chemistry Education Research (CER) started, much like PER, through the discipline of chemistry where teachers began publishing papers on their experiences in teaching, opinions on how to teach and suggestions on experiments to use in lab classes (Cooper & Stowe, 2018). Much of the available research in CER is based on a cognitive epistemology guided by previous psychology research such as the work of Kahneman & Tversky (1974). Cooper & Stowe (2018, p. 6054) formulate it: "However, while a deep knowledge of chemistry principles is vital, it is not sufficient: an understanding of the methods and principles of science education, educational psychology, and cognitive science are also necessary".

Much could be said about the progress of research done in CER but I have decided not to delve deeper into CER as that would be a whole literature review on its own. Additionally, I have chosen not to investigate the learning of concepts of thermodynamics relevant to chemistry, such as enthalpy and Gibb's free energy. However, CER and PER do overlap at times so some CER will be touched upon in the literature review:
PER, and Chemistry Education Research, CER, have had a common interest of study for some time, especially concerning how to teach and learn the concept of energy and concepts related to it (e.g. Bain & Towns, 2018; Dreyfus,

Gouvea, et al., 2014; Nilsson & Niedderer, 2013). Some take a general stance on the energy concept (Millar, 2014a, 2014b) and others choose to focus on energy transfer and transformation (Scherr et al., 2016; Taber, 2000) or related concept, like enthalpy (Bain & Towns, 2018; Nilsson & Niedderer, 2014).

More recently, researchers in both PER, CER and to some extent science education research, have joined together to explore the potential usefulness in bringing in new technologies to visualize processes not usually accessible to the human senses (or at least not directly discernable). One such technology is the *IR camera* which with time has become a more affordable and viable choice of technology in teaching concepts like energy transfer (Xie & Hazzard, 2011). Like mentioned earlier on, however, there is a slight difference in focus of the disciplinary content explored in CER compared to PER. While research on thermodynamics education in CER focuses more on concepts such as *Gibbs free energy, enthalpy* and *entropy* (e.g. Bain, Moon, Mack, & Towns, 2014; Nilsson & Nilsson, 2011; Mustafa Sözbilir, 2003), PER on the same main topic has a focus on *thermodynamic cycles* (e.g. Leinonen & Asikainen, 2012; Loverude, Kautz, & Heron, 2002) and concepts such as *heat*, *temperature* and *work* (e.g. D. T. Brookes & Etkina, 2015; Mäntylä & Koponen, 2007; Wittmann et al., 2019). Learning of the latter content is though, to an certain exten, also investigated in CER (e.g. Kizilaslan & Sozbilir, 2019).

In the recent decade, there has been an increased interest of the overlapping domains between physics and other disciplines such as chemistry, and how to build bridges between these domains (e.g. Dreyfus, Gouvea, et al., 2014; Dreyfus, Sawtelle, Turpen, Gouvea, & Redish, 2014; Geller et al., 2013, 2014), mainly after the introduction of *National Generation Science Standards* (NGSS) (Lead States, 2013) in the USA in 2013 which singles out the *energy* concept as one of the *cross-cutting concepts of science*.

Researchers in PER have collaborated with chemists to study the learning and understanding of heat and temperature through *calorimetry* (e.g. Greenbowe & Meltzer, 2003) and curricular material for physics education have been developed in which calorimetry is used to help students distinguish heat and temperature (L. McDermott, 1996) as calorimetry "offers the best opportunity to clarify the distinction between heat and temperature" (Greenbowe & Meltzer, 2003, p. 796).

Other researchers in PER have studied the usefulness in adapting concepts like *free energy* in teaching students in introductory physics about *spontaneity* and the application of *energy analysis* in non-physics contexts (Geller & Daane, 2019). By studying how students struggle with reconciling the idea of energy conservation and that the usefulness of energy diminishes over time, Geller & Daane (2019) come to the conclusion that energy should be taught in the light of free energy, for example by being explicit with the *substance metaphor* and include *energy distribution* as part of representations of energy such as *energy bars*.

3.2 Learning of thermodynamics

This part of the literature review is mainly based on the summaries of work in PER on the learning and understanding of *heat*, *temperature*, *energy* and *thermodynamics*.

Three resources give a nice overview of the research in PER on the learning and understanding of heat, temperature, energy and thermodynamics: A resource letter on PER written by McDermott & Redish (1999), a resource letter on thermodynamics education research by Dreyfus et al. (2015), and a special issue of *American Journal of Physics* on the energy concept (Meredith & Ruzycki, 2019) . They constitute the core from which the majority of the papers in this review are taken. The section on *Heat, temperature, and thermodynamics* was chosen from the first resource letter. Additionally, some papers from a review on misconceptions of heat and temperature (Sözbilir, 2003) have been selected. Additional papers have been added from the references of the papers in the mentioned resource letters. The papers that have not been available to me have been ordered as physical copies whenever possible. A couple of papers were not available at all, for example *"Work' and 'heat': On a road towards thermodynamics* by von Roon, van Sprand and Verdonk (1994). All papers have been reviewed and added to a master table which includes the authors, the content that is being taught in the paper (e.g. energy flow, adiabatic compression, chemical bonds, the ideal gas law, etc.), the activities (if such exist in the paper) that have been used to teach or test the knowledge about the content, the participants learning about the content (if the paper is empirical), a longer description of the results and conclusions of the paper, a short summary in one or a couple of sentences and keywords (e.g. *K-12*, *context*, *chemistry & physics*, *NGSS*, etc.). The papers were then added to different categories, emerging from the similarities (including the keywords) of the papers, in a new table (for example *Contexts & observable features*, *Language, metaphors & wording, Proposed teaching sequences*, *Barriers*, and *Thermal equilibrium).* The categories that frame my research were then chosen for subsections of the literature review on *Learning thermodynamics* and added to new separate tables for each category (see *Table 1*, *Table 2* and *Table 3*).

A final note before moving on: Research on learning concepts such as enthalpy and Gibbs free energy, or concepts such as entropy and work, has been left out from what is presented here as those concepts are not part of what my research aims at studying the learning of. However, education research on these concepts may be included when necessary such as when the concept of work acts as an obstacle for students in understanding energy (Driver & Warrington, 1985).

3.2.1 Thermodynamics as a physics topic

The branch of physics called *thermodynamics* concerns answers to questions such as "How is it possible to keep our food in the refrigerator at a lower temperature than the kitchen surrounding it?", "How is it possible to increase the temperature of a sheet of paper with just a glass of water at room temperature?", "How is heat transferred?", and "What do heat, temperature and energy really mean?".

In this thesis I refer to the physics content as thermodynamics but it also includes adjacent or overlapping fields such as *thermal physics* and *calorimetry*. The research on learning and understanding concepts such as energy and heat has been a part of the PER activities since the early days of the field (early days as in the acceptance of the field within the physics discipline) (L. C. McDermott & Redish, 1999). Much of the current research in PER that concerns the sub-field focuses on the learning and understanding of the concept of energy.

Thermodynamics is a field of physics that is also important for, and therefore taught to students in, chemistry and engineering. It is a field that, although its modern iteration was developed throughout the 19^{th} and 20^{th} century, a central part of it, namely the concept of *energy*, has been described by textbooks in the same way since the 1860's (Hecht, 2019). However, it was during these two centuries that a paradigm where energy is conserved but degraded, or becomes less "useful", through *transfer* and *transformation*, was established. Before that, the word energy was not used, as the technical term was first used in 1807 (Muller, 2007).

The two central concepts in thermodynamics before the 19^{th} century were force and heat and heat was described through the *Caloric theory*, in which a fluid, called *caloric*, flows from hot to cold bodies. The idea is still today used, as a metaphor, in teaching the concept of energy (e.g. Scherr, Close, McKagan, & Vokos, 2012) and by physicists talking about heat as in "heat is transferred from A to B" (D. T. Brookes & Etkina, 2015, p. 765). The metaphor can be a powerful resource in that the words energy and heat are used in everyday situations as a substance by most people (e.g. "I still have some energy left" or "Don't let the heat out") and thus supports the understanding of the conservation of energy (which is leveraged in teaching activities such as *Energy Theater* (Daane, Wells, & Scherr, 2014). However, some researchers (e.g. Brookes & Etkina, 2015) have urged teachers to be cautious with how and when technical concepts are used: for example, the use of the substance metaphor could lead learners into believing that heat is a state function.

The primary concepts involved in thermodynamics can be described through the *laws of thermodynamics*: Basically, the *zeroth law of thermodynamics* deals with thermal equilibrium and temperature, the first law deals with conservation of energy and the *second law* deals with spontaneity and entropy.[5]

Regarding the physics content, my research concerns the concept of energy in relation to heat, temperature and phase transitions. The physics content of my research thus belongs to the field of physics known as thermodynamics. However, energy is a concept used in multiple fields of both physics and chemistry and it should therefore be noted that a lot of the research done on the learning of the concept of energy uses other fields as a basis for the studies, for example mechanics and kinematics (e.g. Harrer, 2019; Lawson & McDermott, 1987) that at times overlap with thermodynamics.

Heat is the concept for the process of transferring energy by means of temperature differences between multiple systems, and the amount of energy transferred in that process. Among "experts" (in this case researchers in the disciplines of science) there is not really a consensus on what the term heat means (Slisko & Dykstra, 1997): Is heat a *process* (heat transfer) or a *form of energy* (heat energy)? As heat is not a *state function*, it is typically referred to as a "special form" of energy when used in the latter sense (D. T. Brookes & Etkina, 2015). Brookes & Etkina (2015) describe the the quantity of heat, *q*, as how much energy has been added or removed in a thermodynamic system after the process of *heat transfer* (*heating* in their terminology).

Heat transfer does not, however, always imply a change in temperature of the system. This may be confusing to learners with difficulties of separating the concepts of temperature and heat, which several studies have shown to be true for students ranging from children and high school students to chemistry and physics introduction courses at university level (e.g. Erickson, 1979; Greenbowe & Meltzer, 2003; Warren, 1972). Muller (2007) describes a historical experiment that still has some influence on today's thermodynamics: similar to some students thinking of temperature as a measurement of heat (Kesidou & Duit, 1993), an experiment in the 18th century led physicist Joseph Black to conclude that through the process of heating, the quantity of heat can be measured and its intensity is measured as temperature. He called the quantity of heat required to melt the ice *latent heat*. Latent heat is still a common technical term used for the amount of energy required or released during phase transition. The term may however strengthen the belief that heat is a substance that is "hidden" or latent within a material.

To appreciate many of the phenomena in thermodynamics, students need to be able to separate temperature and heat:

In order to even begin teaching about phase transitions, thermodynamic processes and heat engines, students need to be able to at least entertain the idea that it is possible for $\Delta T \neq 0$ without heat transfer ($q = 0$), as for adiabatic expansions, and vice versa; $q \neq 0$ while $\Delta T = 0$.

[5] The third law deals with the entropy of a system as its temperature approaches absolute zero.

During phase transitions, energy is transferred through heat transfer from or to the matter undergoing the process, as latent heat. The phase transition happens without changing the temperature of the substance undergoing the phase transition, e.g. some ice melting will require energy from the surroundings and the temperature of the ice and the surrounding water will be kept at $0\ ^0C$ until all the ice has melted (before it start increasing towards the surrounding temperature). However, the two phases do have the same temperature during the process and this is important partly in understanding why we, for example, in slowing down the temperature change of a lemonade, keep some ice cubes in it even though it has just been taken out from the refrigerator. This is made very explicit when consulting the numbers: by examining how much energy is needed to 1) increase the temperature of water from $4\ ^0C$ (recommended temperature in a refrigerator) to $37\ ^0C$[6], versus 2) how much energy is needed to melt the same mass of ice, one finds that the difference is quite large. The two amounts of energy are required for two different objectives: for the liquid water (the lemonade) it is needed to raise the temperature and for the ice, it is required to break the lattice structure so that the solid changes into a liquid. The values for c in 1) and L in 2) come from The Engineering ToolBox

1) For 0.5 kg water (lemonade):
$E = m*c*\Delta T$, where E is the thermal energy transferred to increase or decrease the temperature, ΔT, of a mass, m, of water. c is the isobaric specific heat capacity for water (assumed to be constant between 4-37 ^0C)[7]
m = 0.5 kg,
ΔT = 33 K,
c = 4.180 kJ/(kg K) (Engineering ToolBox, 2004) →
E = 0.5 kg*4.180 kJ/(kg K)*33 K = 68.970 kJ

2) To melt 0.5 ice: E = L*m, where E is the thermal energy required to melt the ice, L is the heat of fusion for water and m is the mass of the water.
M = 0.5 kg,
L = 333.55 kJ/kg (Engineering ToolBox, 2003) →
E = 0.5 kg * 333.55 kJ/kg = 166.775 kJ

This is more than twice the amount of energy needed to increase the temperature of the lemonade by 33 ^0C.

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[6] Close to the average body temperature. A liquid of this temperature is experienced as lukewarm.

[7] The isobaric specific heat capacity for water at 10-40 □C varies between about 4.196 and 4.180 kJ/(kg K)

If a learner understands that it is possible for $\Delta T = 0$ while $q \neq 0$, it is also possible to grasp that, to 1), a relatively large amount of energy is required in heating the ice enough to make it all melt and that during this process, the temperature will stay constant. Another way to illustrate the difference between the amount of energy needed to increase T within a phase and to transition into a new phase are temperature-energy diagrams. They do, however, assume a constant pressure (other types of phase diagrams are needed to show how phases change with varied pressure and temperature).

A process related to phase transition is *deliquescence* (and *hygroscopy*). A hygroscopic material will (at a certain humidity) take up water from the surrounding environment and in the case that the material absorbs the water to form aqueous solution, it deliquesces (the liquid water reacts with the material). A salt reacting exothermically with water would then transfer energy through heat transfer to the surroundings as the water vapour is absorbed (similar to an exothermic reaction). Additionally, the absorption may transfer energy through heat transfer as latent heat of condensation (basically the water vapour condensing in the material). These phenomena are important for industries ranging from medicine to textile (e.g. Lau, 2001; Rengasamy, 2011).

3.2.2 Energy as a cross-cutting concept

Research have shown that there are important differences between the disciplines in how the subject-matter of thermodynamics is understood and taught. For example, by analyzing thermodynamics textbooks common in introductory courses in each discipline, Christiansen and Rump (2008) showed that *open vessel systems* (like a beaker with salt dissolving in water) are more common in physical chemistry. In contrast, *closed systems* (like a cylinder with a piston) are more common in physics teaching. This could be explained by what Thomas Kuhn (2012) refers to as the *paradigms* (a core of theories and models accepted by the discipline).

As a response to these differences, there has been calls for finding a common ground in multiple disciplines when teaching, what Star and Griesemer (1989) refer to as *boundary objects* (see Glossary):

Cooper et al. (2015) mention the energy concept as one of these core ideas that need to be taught coherently across multiple disciplines to be better understood by the students. Duit (1981) argues that the concept of energy, in physics education, needs to be taught in a more general sense, relating it to notions such as heat and disciplines such as chemistry, rather than restricting it to work and mechanics as it otherwise is difficult for students to learn about energy conservation and degradation.

The Next Generation Science Standards (NGSS) (Lead States, 2013), that were presented in the USA in 2013, outlines this kind of vision for a range of science topics including the energy concept. In line with the vision of cross-cutting ideas, the NGSS emphasize the *knowledge-in-use* in multiple contexts and across many phenomena. This emphasis can also be found in European science standards such as the *German science standards* (Kubsch et al., 2019) or the *Swedish syllabus for physics* in upper-secondary school education (Skolverket, 2011).

Since the American standards were introduced, many studies in PER on learning and teaching the energy concept have used the new standards as an argument for the importance of their research (e.g. Geller & Daane, 2019; Goodhew, Robertson, Heron, & Scherr, 2019; Gray et al., 2019). In one of these studies, Dreyfus et al. (2014) show that students being taught the energy concept within these *disciplinary silos* have a hard time reconciling what they are taught in physics with what they are taught in biology regarding ATP and the net output of energy when breaking and forming chemical bonds. In another paper, Dreyfus et al. (2014) proposes a way for teaching about *chemical energy* in a coherent way across physics, chemistry and biology.

Another goal of NGSS is a science education in which students practice science as professionals would. For physics, this has been interpreted by Robertson et al. (2019) to prescribe that when physicists teach physics teachers they should strive to take their students' ideas seriously as a physicists would, and then help them to find ways for testing the ideas or in other ways support their reasoning process. This would then teach the physics teachers to treat their future students' ideas as serious. By accepting the initial ideas as starting points, Robertson et al. (2019) show that it is possible to add instructor moves to support the reasoning process in a generative way. Such instructor moves could for example be constructing analogies and connecting experiments to familiar phenomena, suggesting experiments to test the ideas and drawing on concepts that may be used to check for coherence.

In 2018, one of the earlier mentioned platforms for communicating modern research in PER, the Physics Research and Education Gordon Research Conference aimed at highlighting and collecting the modern research on the teaching and learning of the energy concept and related content by taking on the theme *Novel Research in Energy Topics, and Transformative Methods for Teaching Undergraduate Students About Energy Concepts*. The conference led to a special issue of *American Journal of Physics: On Teaching of the Subtle Concept of Energy*, which collects much of the modern research on the teaching and learning of the energy concept, and related concepts such as heat and temperature.

3.2.3 Students' understanding of heat

How students and pupils understand energy and heat are hot topics within Physics Education Research. The concept of heat is quite abstract and is often confused with temperature (e.g. Erickson, 1979; Warren, 1972) and other concepts or properties (Sözbilir, 2003). The topic of how to teach heat, temperature and thermodynamics has been a part of PER for a long time (L. C. McDermott & Redish, 1999). In an early PER study, Warren (1972) showed the difficulties students, in various science programs, have in understanding internal energy and heat. A common definition of heat among the participants in the study was that it is just another *form of energy*.

Misinterpretations of heat transfer results in difficulties understanding how some matter changing phase can have a constant temperature during the transition and still transfer heat (latent heat), or how it is possible to hold a sparkler without being burnt by the sparks that may have a temperature of 2000 ^{0}C. Objects with different *thermal conductivity*, but the same temperature, are perceived as having different temperatures as learners use their *sense of touch* as indication of the temperature of the object, thus misinterpreting the experience. In regards to this confusion, Erickson (1979, p. 59) once wrote "If pupils were able to 'see' this phenomenon in terms of a transfer of energy from their body to the object, this sort of situation would likely be less of a problem than it seems to be at present".

In the framework applied by us physicists (Kesidou & Duit, 1993), energy is something that is *transferred* and *transformed*. The total amount of energy is always conserved but a degradation occurs in transfer and transformation which thus makes the energy "less useful". The last part is, however, not always understood by students: According to Hecht (2019), many physics textbooks do not directly define the concept but choose to rather circumvent giving the definition by referring to another quantity like work, as in "energy is the ability to do work". This explanation, together with the law of conservation of energy, could be a potential source for confusion among students and could be a possible (although incorrect) argument against sustainable development ("Why do we need to be sustainable if energy always is conserved and energy can be used to do work with?") (Geller & Daane, 2019). Other studies (e.g. Driver & Warrington, 1985; Duit, 1981) have also warned of the problems with connecting the concept of energy to work when teaching about what energy is.

Feynman also found it difficult defining what energy is as can be read from one of his lectures:

> *[...] there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same.*
> (Feynman, Leighton, & Sands, 1989, pp. 4–1)

He did, however, in the same chapter, make an analogy in which energy is represented as blocks owned by a small boy, metaphorically representing energy as a substance (Amin, 2009). The boy's mother counts the blocks each day but sometimes some of the blocks are missing. She suspects that the missing blocks have been thrown in some dirty water in the bathtub. She does not want to put her hands in the water so she formulates an equation to check if the amount of blocks are conserved (she knows the original height of the water and how much each of the blocks would raise the water level).

Feynman goes on describing how the different ways of hiding the blocks could be analogies to the different forms of energy and how the analogy relates to the conservation of energy. What he does not mention in the analogy though is the degradation of energy. This could potentially be added if it would be assumed that the blocks are painted: when they are thrown in the water, the paint is washed off and the blocks thus become less useful to the boy.

Like the word energy, heat has many uses in everyday situations where it differs from the scientific or technical use of the word. In addition, just like when encountering the energy concept in physics, this causes confusion among students when they encounter the concept of heat in the discipline of physics as they may equate heat with temperature or think of temperature as a measurement of heat (Erickson, 1979; Warren, 1972). It has also been shown (D. Brookes et al., 2005; Hecht, 2019; Leite, 1999; Summers, 1983; Warren, 1972; Zemansky, 1970) that textbooks are particularly bad at explaining heat or giving definitions for the concept that helps students in distinguishing heat from temperature. If textbooks give bad explanations, students tend to keep their initial ideas about energy after physics instruction (Duit, 1981) and temperature is though of as a measurement of heat, then perhaps we have to begin considering what the initial ideas about heat is for learners. This is the topic for the next section of the literature review.

3.2.4 The role of personal and embodied experiences in learning about heat

A way of "experiencing" the abstract quantity of energy is through transformations and transfers such as heat transfer or the transformation of chemical energy in our body to kinetic energy when compressing a spring (it may feel exhausting). But how do students understand these experiences? Clough & Driver (1985) show that students tend to use their *bodies* as reference when reasoning about the direction of conduction of heat. This made it difficult for the students to relate what they felt as cold to conduction of heat. Adding to this, Thomaz et al. (1995) show that some students think of heat as a sensation. To then learn that there are phenomena in which temperature changes without heat transfer, like an adiabatic expansion of a gas, or where there is a heat transfer but the temperature does not change, like in phase transitions, may be very confusing for these students. Other studies (e.g. Frederik, Valk, Leite, & Thorén, 1999; Lewis & Linn, 2003) have found similar conceptions of heat among students.

Adding to this, Carlton (2000) proposes and tests a teaching sequence that supports students in reconciling their *embodied experience* (i.e. what they feel with their hands) with what physics tells us (i.e. the zeroth and second laws of thermodynamics). The sequence starts out by providing the students with two conflicting experiences of "hot" and "cold": The students are to put their hands in two bowls of water of $0\,^0$C and $55\,^0$C to move both hands to a bowl of water of $42\,^0$C, thus making the students experience both "hot" and "cold" in the same body of water at the same time. They are then to discuss what happens with the temperature of the water in the bowl when we let them stay in the room for a longer time. This leads the students to a discussion on heat transfer and the zeroth/second law of thermodynamics. The final steps can be summarized as:

- The students' intellectual conviction is tested against their confidence in sensation as a good measurement.

- Thought experiment, to separate temperature from heat, in which a kettle of boiling water is poured into a sea during winter. They are then to answer whether it will raise the temperature of the sea to the same as during summer time (it is emphasized that the temperature of the boiling water is much higher than the sea during summer).

- Measurement of temperature of ice water to show thermal equilibrium during phase transition.

- Definitions of heat, latent heat and temperature are then given: heat as change in internal energy, temperature as change in average kinetic energy and latent heat as change in potential energy for molecules.

The majority of students participating in the sequence were able to discuss heat, temperature and thermal equilibrium in a scientific way. Carlton (2000) does, however, describe heat flow as a process where energy transfer is the result of a temperature difference (and heat is the energy that is transferred). Although acknowledging the contributions of the teaching sequence, such as the emphasis on making learners' prior knowledge explicit, Taber (2000) critizes this simplifaction, made by Carlton (2000), and warns that it will lead to students believing that internal energy is heat and that temperature indicates the concentration of heat. Taber proposes a teaching scheme in which heat is energy that is being transferred between bodies of different temperature which either results in a change in temperature or a change of phase. On a molecular level, heat transfer increases the internal energy of the particles and the internal energy can be kinetic and potential. As such, a change in internal energy is a change in kinetic and potential energy (the latter case lead to latent heat and phase transition). Finally, temperature is defined as the kinetic energy of the particles. Taber proposes this as a consistent way of relating heat and temperature but do add that it is not a complete scheme. Taber does, however, agree with Carlton in that it is important to start out from students' existing ideas in constructing a scientific understanding. In Carlton's sequence, this means to base the learning in embodied activities such as feeling something with the hands.

Other activities have been proposed that align with the idea of leveraging embodied experience in learning about energy transfer. This is the topic for the next section of this literature review.

3.2.5 Ways of teaching about energy transfer and transformation

Representing energy as blocks is just one way of representing energy through the substance metaphor. Other ways of using this metaphor in teaching about energy have been proposed: for example *Energy Tracking Diagrams* (Scherr et al., 2016), *Energy Cubes* (Scherr, Close, Close, & Vokos, 2012) and *Energy Theater* (Daane, Wells, et al., 2014; Scherr, Close, Close, et al., 2012), all of which have a goal of reinforcing the understanding of conservation of energy (Geller & Daane, 2019) for which, according to Scherr et al. (2012), the conceptualization of energy as a substance has a special advantage in teaching.

In Energy Theater, each participant represents an unit of energy and an energy type. Every enactment represents a transformation from one energy type to another, or a transfer of energy between objects. The activity is based around a specific physical scenario.

Similar to Energy Theater, and to Feynman's analogy with the blocks, *Energy Cubes* is an activity in which small cubes represent energy units and energy types. The cubes are placed within regions on a paper or whiteboard, each representing an object. The cubes have letters on each side representing a different type of energy. The cube is moved to represent transfer, and flipped to represent transformation. These processes are represented as arrows in *Energy Tracking Diagrams*. Objects are again represented by regions on a paper and the letters of the cubes are instead written on the paper next to the arrows. It is thus possible to track the full process of, for example, a hand pressing a spring: One energy type (chemical energy), in an object (a hand), transforms into a second type (kinetic energy), to then be transferred to another object (spring), and there transform into a third type (elastic energy). Type of transfer or transformation can be indicated by a color of the arrow. In contrast to the other two ways of representing energy, Energy Tracking Diagrams have the advantage of giving a full overview of the process from start to end in one image.

These activities capture the basic aspects of the energy concept that Duit (1984) claims facilitates understanding of energy in real world problems:

1) *The conception of energy*
2) *Energy transfer*
3) *Energy conversion*
4) *Energy conservation*
5) *Energy degradation*

Duit (1984) later argues that energy degradation should be given priority in teaching over energy conservation as energy degradation may support the understanding of energy conservation and energy conservation often contradicts everyday experience. A similar argument is made by Kesidou & Duit (1993) but they also add that, based on their findings "science instruction should emphasize the ideas of energy transformation, energy conservation and energy degradation […]" (Kesidou & Duit, 1993, p. 100) rather than focusing on energy forms. In line with this, Nordine et al. (2019) claim that many students struggle with interpreting the world through an energy perspective because of their confidence with energy forms.

This overreliance on the forms of energy acts as a *barrier* in explaining how and why phenomena occur, that is through the transfer and transformations of energy within and between systems. To avoid the barrier, Nordine et al. (2019) propose a new approach to teaching energy, which they call the *systems-transfer approach*. In this approach, phenomena are analyzed through the systems, the types of transfers and transformations rather than the energy forms involved in the phenomena. For example, the phenomenon involved in using a solar cooker would be described as light energy being converted into thermal energy to cook the food from a forms perspective while in a systems-transfer perspective it would be described as energy being transferred to the food in increasing the temperature of the food. The energy is transferred as light from the sun.

Another study (Neumann et al., 2013) suggests that students first develop the understanding of energy sources and forms of energy and only later an understanding of transfer and transformation (which is developed along with understanding degradation). Additional results from this study suggest that the contexts of problems in physics affect how students answer. That is, a student who answers correctly on one problem may not be able to do it if the same problem is given in another context.

Traditional results showing that students understand energy transformation early on in education (Duit, 1981) and that students have difficulties with understanding the concept of energy and energy transformation (Dawson-Tunik, 2006) may seem contradictory but Neumann et al. (2013) suggest that the opposing results come from the different contexts that were used when probing the students in each study. The context affects how we understand problems involving energy.

3.2.6 The role of contexts, framing and resources in thermodynamics education

Following the Resources framework, proposed by Hammer (2000), and Knowledge-in-Pieces by DiSessa (1993), some research in PER has explored whether contexts matter in what traditionally has been thought of as misconceptions. Hammer et al. (2004) describe the relationship between students' expectations and the context as *framing*. How one student and an instructor or group of students frame a problem may vary which then affect what resources are applied to the problem and what is noticed. However, Redish et al. (1998) showed that students' expectations of physics change after introductory physics, i.e.. they frame physics as a discipline in a new way after having studied it: Physics is experienced both as *less coherent* and *less relevant* to their personal experience. The authors warn of the consequence the change in experience may have on the students' future learning and understanding in physics: The changed view of *coherence* may cause students to fail to notice errors and make them unable to evaluate through crosschecking. The changed view of the *connection to reality* can have serious consequences on the evaluation of answers to physics problems as it would not matter for a student if an answer to a physics problem in which a person reaches a speed of 8000 m/s, by just jumping of the ground, sounds reasonable or not. However, Scherr & Hammer (2009) propose that the context of the study (answering a survey) of Redish et al. (1998) may have affected the students in a way that it is difficult to actually conclude anything about how the students reason in the context of the course when encountering physical phenomena, e.g. students answering a survey does not necessarily reflect how the students reason about physical phenomena.

The research on how *contexts* influence reasoning is important as it tells us something about how students may frame a situation. A full list of the papers I have reviewed that involve how contexts affect reasoning about energy or thermodynamics can be found in *Table 1* (at the end of *3.2.6*).

Duit (1981, 1984) shows that the *cultural context* may play a role in how students conceptualize energy: for example, while German and Swiss students associate energy with *fuel*, Philippine students associate energy with *strength*. However, Duit (1984) adds that it can not be completely determined if this is because of the cultural contexts, or if it has to do with languages. Colonnese et al. (2012) suggest that this cultural aspect of the energy concept is a reason for why researchers, despite much research on how to teach the concept of energy, can not agree on a curricular proposal.

As shown by Dreyfus et al. (2014) cultural contexts are also influential in students' reasoning when they move between disciplines: it is possible for students to hold multiple seemingly contradictory ideas as they depend on the disciplinary context. For example, for some students *ATP hydrolysis* can be thought of as involving energy to break bonds (from a physics perspective) but from a biology perspective, it is thought of as involving energy being released when chemical bonds break. The students can apply the appropriate perspective in the corresponding context but find it difficult to reconcile the different perspectives.

A contextual factor that we humans always carry with us is the *human body*. Some research shows that there is a tendency to associate heat and related concepts to *embodied experiences* (e.g. Clough & Driver, 1985; Frederik et al., 1999) such as *cold* (e.g. Lewis & Linn, 2003) and *softness* (Clough & Driver, 1985; Erickson, 1979). For example, Clough & Driver (1985) show that students relate direction of heat conductivity to their bodies: It is difficult to think of conduction of heat when feeling cold. A similar result is found by Lewis & Linn (2003): When asked what material would be good in keeping a cold object cold, adults a large majority responded with aluminum foil as it has a "frozen feeling" and that it holds "cold air". Erickson (1979) and Thomaz et al. (1995) show similar findings in that the participants in their studies used cold as a substance that is the opposite to heat.

Another influential factor when it comes to our thinking of heat and related concepts framed by our embodied experiences is air: We are in constant contact with air in our everyday lives and this seems to relate air to our bodies and conceptions of heat as learners may associate thermal phenomena and "cold" with air (Erickson, 1979; Lewis & Linn, 2003). However, as suggested by Wittmann et al. (2019), air may also inhibit students' analysis of energy transfer and transformation as air is not thought of as something energy can flow into. In contrast, in another context (clinical interviews) with other participants (adults[8]), air is something that holds cold, whch can be illustrated in an explanation of why one would choose aluminum foil to keep soda cold: "cold air can't escape out of the aluminum." (Lewis & Linn, 2003, p. S165).

Adding to this approach, by basing a study on the *systems-transfer approach* of teaching energy, Kubsch et al. (2019) compare the relation of integrated knowledge with *knowledge-in-use*, i.e. the ability to interpret real world phenomena through disciplinary core ideas and scientific practice. The concept of *integrated knowledge* is partly based around research by Chi et al. (1981) and Hmelo-Silver & Pfeffer (2004) showing that experts and novices differ in how the perceive a specific phenomenon in that expert-like[9] knowledge is well-organized around some *core ideas* (integrated knowledge) such as energy conservation, and the knowledge of novices[10] relies on *surface features* of problems. In contrast, Lewis & Linn (2003) show that for problems

[8] One of three groups studied. The other two groups being chemists & physicists and middle school students.

[9] Expert are in this case, like in the paper by Chi et al. (1981), PhD students and more experienced members of the disciplinary community.

[10] Novices refer to, like in the paper by Chi et al. (1981), undergraduate and less experienced students in the disciplines.

in everyday contexts, even experts[11] rely on everyday knowledge for explanations.

Dreyfus et al. (2014) suggest using chemical energy as a cross-cutting concept to help students reconcile ideas across disciplinary contexts such as physics and biology. Wittmann et al. (2019) studied some middle school students working with problems in which they were supposed to answer questions on energy transfer across different contexts (a metal rod in a box of ice "feeling cold", a "warm" soda can in a bucket of "cold" water, etc.). The results showed that contextual aspects, such as choice of system for the problem, matters. Two of the problems were of similar nature but were answered by the students in quite different ways: the first one concerned a box sliding across a floor and the other one was about a pendulum swinging. Both of the problems involved reasoning about why the objects would stop moving. Even though both included a list of potential answers in which the conservation of energy through transformation and transfer of energy was one, 59% of the students answered that energy was "used up" in the problem with the pendulum while only 25% gave that answer for the problem with the box. 43% chose an answer in line with energy conservation for the problem with the box in contrast to 29% of the students for the problem with the pendulum. The authors speculate that this has to do with the contextual aspect of air (in contrast to "ground" for the box) being present in some of the alternatives to answering the problem with the pendulum: The resources associated to air in the pendulum-problem inhibit, e.g. act as barriers to, the resources the students use in the box-problem to understand it as a problem involving energy transfer.

There are indications that contexts affect reasoning not only for learners but also for experts in a discipline (researchers and teachers) as shown by Lewis & Linn (2003) in a study where they contextualized a problem with an everyday setting and experts were able to make the predictions but found it difficult to make explanations. One participant ended up applying an everyday memory to the problem to make an explanation for a task contextualized in an everyday situation.

Table 1. Contexts, framing and contextual aspects in learning about thermodynamics. My own comments are put within brackets.

Publication	**Summary**	**Example**
(Wittmann et al., 2019)	Student reasoning depends on *context* and *system* represented in energy problems. Further	Similar pendulum & box-problems (they come to a stop). More common with energy conservation-responses for box, far more

[11] In this study, the experts were either researchers or teachers in physics and chemistry at college or university level.

	research on contextual factors is encouraged.	"energy used up"-responses for the pendulum. Energy transfer to ground is easier to comprehend than to air.
(Dreyfus, Sawtelle, et al., 2014)	*Disciplinary context* affects reasoning about energy.	Students can have multiple, contradictory ideas, such as chemical bonds breaking requiring energy and releasing energy, that are applied depending on context (physics and biology).
(Chi et al., 1981)	Expert rely on core ideas in problem solving, novices focus on *literal features* of problems.	Experts classify according to principles (Law of Conservation of Energy and Newton's Second Law). Novices grouped problems with the same object (spring), literal terms (friction) or configuration (block+inclined plane)
(Clough & Driver, 1985)	Students use *observable features* to explain heat conductivity.	Color and smoothness of an object is used to determine the heat conductivity.
(Driver & Warrington, 1985)	Students interpret situations to which they are to apply energy conservation, through its *observable characteristics*, such as force and distance	Students are asked to explain how to modify a water turbine so it lifts weights faster. One student responds that it can be done by modifying the height at which it is attached at and that it would result in it being faster and have more force (rather than reason in terms of increased rate of energy input).
(Kubsch et al., 2019)	In participating in the systems-transfer approach, *coherence* of students' knowledge network is increased as students link ideas to energy transfer as a *core idea* and thus manage to	Student analyzing an electric heater and a barrel rolling down a hill with the same set of ideas connected to energy transfer, like temperature increase.

	apply it to different contexts. *Organized networks* are important in activating and connecting ideas across contexts [e.g. framing them coherently].	
(Donaldson, Felzien, Marvin, Cielocha, & Shapiro, 2019)	After attending courses with an interdisciplinary theme across physics, biology and biochemistry. Students seemed to experience the different *disciplinary contexts* as *coherent* in regards to energy analysis [e.g. apply a similar framing across the contexts].	Student relating how to choose system and explain input and outputs (physics) to exothermic and endothermic interactions of molecules (biochemistry), which is then related to molecular structure (Organic chemistry)
(Neumann et al., 2013)	The study show the "*effect of item context*", that is, students are able to answer correctly about energy transformation in some questions but fail at doing so when given a new context.	For example, student providing a correct answer on energy transformation for a skateboarder in a half-pipe but not for another context.
(Lewis & Linn, 2003)	Students, adults and some scientists show similar *context-dependent* responses in explaining *everyday phenomena* but some scientists test different concepts and models. However, in contrasts to students and adults, scientists do give good predictions and respond on multiple levels (microscopic and macroscopic).	Adults and students talking about objects "holding heat". Student arguing that the foil is best to keep something cold but also best for feeling the cold of the object through. When asked if aluminum foil or wool is better at keeping juice cold, a scientist draws on the memory of her/his mother insulating food brought out of the

	After participating in a technology-based curriculum, *anchoring* content in *everyday events*, students improved their understanding of thermal equilibrium, temperature and heat.	oven to explain why aluminum foil is chosen. Instruction starting out with intuitive idea of "spreading out" (e.g. mashed potatoes) leads to "cooling down faster".
(Nilsson & Niedderer, 2014)	Students interpreting [framing] apparatuses in a task in different ways lead to different logics being applied: the "flow" in the apparatus fore fronted, viewing both systems as static (based on the pictures) thus describing them as states instead of processes or interpreting them as open or closed systems (potentially based on descriptions of open or closed taps) thus allowing for change in matter.	Two apparatus, closed and containing magnesium metal and hydrochloric acid (one with constant pressure and one at constant volume) were visually presented to students. Students were asked what apparatus (of two) gives off most heat to the surroundings and in which one energy transferred as heat is equal to the reaction enthalpy. Student interpreting [framing] apparatus as an open or closed system added the potentiality of being open (through a valve), rather than a closed system of constant pressure.
(Geller & Daane, 2019)	A focus on energy conservation in teaching may create problems [in coherently framing across contexts] when students are to apply the ideas on *contexts outside of physics*, for example in a *sociopolitical context* as they may then apply free energy as if it were a type of energy to be in accordance with the principle of energy conservation.	Students applying the ideas of "energy comes in forms", "energy is conserved", "energy is the ability to do useful work" and energy is located in an object" as taught in intro. Physics. In this context (usefulness of energy) it leads to confusion. For example, teacher explaining that free energy has to be conserved when asked if the total useful energy in the universe is constant.

(Arnold & Millar, 1996)	Successfulness in applying one and the *same model for different contexts* vary among students. However, contextualizing science as a *story* (story-based approach) lead to improved learning (students were able to apply the "story" weeks later [they framed it as a story]).	Students successfully extended the story to other situations [framed new situations as "stories"]: for example when asked of the outcome of switching on an electric fire in a cold bedroom a student responded that the room is like a box and heat goes out in the room. The heat coming in to the room is eventually equal to the heat going out [water level in the story].
(A. A. DiSessa, 2014)	A *shift of context* is a potential mechanism in learners' conceptual development [e.g. to learn how to frame coherently across contexts thus applying p-prims or resources relevant for multiple contexts in those contexts].	A student explaining why a graph of temperature versus time (hot or cold water in test tube equilibrating in a bath of room-temperature water) went from being steep to less step with time (from a high to a lower temperature) use a "freaking out" model (steep curve represent liquid freaking out and less steep means that the liquid calms down) which include the abstract balance p-prim. This p-prim is usually cued by spatial symmetry but this phenomenon does not include a spatial component. The students have shifted the context in which the p-prim is activated.

3.2.7 Productive resources

From the point of view of the Resources framework, Redish (2014, p. 544) refers to resources as "ways and tools of knowing". If a resource supports an understanding that leads to a, for the discipline or for the purpose of the specific teaching situation, sound answer, then the resource is said to be *productive*. Productive resources in the literature include *exemplars*[12] or *prototypes*[12] of everyday experiences (Robertson et al., 2019), such as pouring up soup in a bowl to understand heat transfer (Lewis & Linn, 2003), cultural resources such as "fuel" in associating energy with fuel (Germany) or "strength" in assocating energy with physical activity (Philippines) (Duit, 1984), phenomenological primitives such as "abstract balance" in understanding thermal equilibrium (A. A. DiSessa, 2014) or teaching sequences leveraging some of these productive resources in teaching about energy and temperature (Mäntylä & Koponen, 2007; Tobin et al., 2019). An overview of some results on this topic can be found in *Table 2* (at the end of *3.2.7*). It is possible to discern the nature of some of the productive resources in the literature review, for example that thermal equilibrium seem to be a type of *threshold concept* (Meyer & Land, 2003) that support the distinction of heat and temperature (Carlton, 2000; Duit & Kesidou, 1988; Thomaz et al., 1995). A learner may not be able to distinguish between heat and temperature by learning the concepts separately but through thermal equilibrium they will have a relationship between the two concepts which leverages the distinction of the two concepts, e.g. if one knows that objects (metal and wood) in thermal equilibrium have the same temperature but that they still feel different (cold and warm) it has to do with the heat transfer, not the temperature. Other resources include exemplars and prototypes of everyday situations (Lewis & Linn, 2003) such as a blowing fan, the weather of Seattle and computer fans (Robertson et al., 2019).

Some resources may, however, inhibit other resources or lead reasoning astray from the reasoning that could have been productive for meaning-making (in terms of the learning target set by the teacher). There is yet no term for this type of resource but a common way to refer to them is as *barriers*[13] (Loverude et al., 2002) which is the term I have chosen to use for the next section of the literature review which reviews some of these constructs and how the inhibit learning and understanding of thermodynamics. Barriers are context-dependent and examples of barriers include the substance metaphor when learning about heat: It may be a *productive resource* in understanding energy conservation (Scherr, Close, Close, et al., 2012) but may act as a *barrier* in understanding heat as a process (as heat as a substance leads one to

[12] The resources are not referred to as exemplars or prototypes by Robertson. This is my own terminology in this case that I have applied to relate the paper to the wider research on resources.
[13] Like resources, barriers refer to resources of a cognitive nature. However, I am at times referring to an object in the environment or in a written task as a barrier. What I really refer to then is the associated resource to this object. This association may differ between individuals or groups but the barrier characteristics are shown through the reasoning of the individual or group (e.g. does the reasoning seem to move away from the intended target of the explanation or lead to the reasoning coming to a complete halt?). For example, the substance metaphor is a barrier in some cases in that it is associated with some resources (the actual barriers) that hinder or distract productive reasoning. Such an association could be that substances "drip" which leads to the conclusion that energy "drips".

believe that heat is a state function (D. Brookes et al., 2005). Here a metaphor relating to currency may be a more productive resource (which is productive for explaining both energy conservation and degradation (Daane, Vokos, et al., 2014)).

Table 2. Resources in learning about heat, temperature and energy. The authors may have used other terms than "productive resource" in describing the learning potential of the constructs (e.g. metaphors, concepts, etc.) in their papers.

Publication	**Summary**	**Example**
(Tobin et al., 2019)	*"Air"* as a productive resource in reasoning about dissipation.	When a pompom is being tossed up into the air and discuss what happens to its energy. Students add "air" to their energy story: Energy dissipate to the surroundings, for example the air and the ground.
(Thomaz et al., 1995)	*Thermal equilibrium* is a productive resources in being able to distinguish between heat and temperature *Experience of "hot" and "cold"* as a productive resource for heat transfer	No qualitative interview data was presented. Initially, students were exposed to their sensations of "cold" and "hot" in relation to temperature (awareness) and then get to measure the temperatures of the objects they have touched. They are also to measure temperature change of two objects of different temperatures being put in contact with each other. A majority of the students taught through the model on thermal equilibrium could give a correct definition of heat (0% before the teaching) and none in the control group could do it.
(Robertson et al., 2019)	*Analogies, experiments* and *everyday situations* as productive resources in learning about heat transfer.	Teachers discussing whether a fan will cool you down or warm you up. The course instructor shares a situation in which it was tested experimentally which lead the teachers to extend the discussion to that of phase transition (evaporation) and heat transfer. The course instructor shares the everyday experience of feeling warm in Seattle even though it is below body temperature which

		allow the teachers to use the weather of Seattle as a productive resource in the discussion. The instructor also add the experience of a computer fan which seem to be a productive resource as the teacher begin discussing relation between body temperature, surrounding temperature and convection
(Duit & Kesidou, 1988)	*Thermal equilibrium* as a productive resource in learning to distinguish heat and temperature.	Students had trouble with understanding temperature equalization (many had the idea that a temperature difference may remain or occur after temperature equalization, and were not able to distinguish heat and temperature. The researchers make the conclusion that learning about thermal equilibrium will support understanding of heat and temperature.
(Carlton, 2000)	*Thermal equilibrium* as a productive resource in learning to distinguish heat and temperature. *Experience of "hot" and "cold"* as a productive resource for heat transfer.	Student presented with three bowls, one "cold", one "warm" and one of temperature somewhere between. Student's hands are put in the warm and cold water and then moved over to the one between the other two to use the experience as a productive resource for learning that feel is not a good measurement of temperature. The student can conclude that there is a transfer of heat which will make the temperature of the water go towards room temperature (thermal equilibrium) and presented with objects of polystyrene and iron, that have been standing in the room over night, that the student get to feel, the student can conclude that what is felt is really heat transfer.

(Mäntylä & Koponen, 2007)	Representing knowledge structure as *network* as productive resource in learning about temperature.	Network representations (NR) are drawn by students, discussed with other students that together draw new network representations and finally each students draw their own network representation. An initial NR had temperature as a central concept with other concepts attached to it (work, pressure, radiation). The final NR was hierarchical with explanations for different levels (micro vs. macro, models and empirical laws).
(Lewis & Linn, 2003)	*Everyday situation* as a productive resource in understanding heat transfer.	Students having an everyday understanding of materials cooling faster when they are spread out on a large surface area, for example from pouring soup in bowls or spreading out mashed potatoes.
(Duit, 1984)	*Language* or *culture* as productive resource in learning about energy.	Philippine students associating energy with strength while German students associate with fuel. When asked for application of the concept, the German students mentions fuels and electricity and the Philippine students mention physical activities.
(Geller & Daane, 2019)	Resources such as *"energy is conserved", "energy is the ability to do useful work", "energy comes in forms"* and *"energy is located in an object*" are productive for thinking of energy as being conserved .	Students talk about energy as bits and the transfer of energy but struggle with accepting that energy can have a level of usefulness.
(Daane, Vokos, et al., 2014)	"Amount" and "value" in supporting understanding of energy conservation and degradation.	Student explaining energy degradation through an example with a block sliding over a floor by referring to the energy amount staying constant but the value being decreased.

(Geller et al., 2019)	Resources from chemistry/biology can be productive in physics and vice versa.	Physics is used by a student to unpack a heuristic from biology: ATP going to ADP releases energy which really is two physical process, one which a bond breaks (requires energy) and one where it forms (releases energy) and the net result is that energy is released which is communicated through the heuristic in biology.
(A. A. DiSessa, 2014)	Near normative scientific understanding of thermal phenomena is composed of naïve conceptions. The p-prim "Abstract balance" as productive resource in understanding thermal equilibrium.	Student applying a freaking out model to explain why a curve in a graph of temperature versus time is steeper at the beginning and less steep closer to the temperature of the equilibrium. The model is based on, partly the p-prim abstract balance.
(Wittmann et al., 2019)	The *substance metaphor* is a productive resource in understanding energy flow.	A majority of students tend to use both coldness flow and heat flow which could productively form energy flow if they are reversed to each other.
(Kesidou & Duit, 1993)	*Energy degradation* is a productive resource in understanding everyday phenomena.	No example given.
(Harrer, 2019)	*Indicator reasoning*, *systems thinking* and *substance metaphor* as productive resources for energy analysis.	Two students managing to explain through an energy analysis, why one ball rolls quicker down tracks of different width ("Quicker speed, less rotation") and draw a Energy-Interaction Diagram to leverage indicator reasoning, systems thinking and the substance metaphor in successfully explaining the phenomenon.
(Bauer & Chan, 2019)	*Everyday experience* as a productive resource for a better understanding of heat and temperature.	Question including "cold" ("is hot-stays-hot and cold-stays-cold as a hypothesis supported by data?") is responded with an explanation in which energy is

	The *particulate nature of matter model*, as a conceptual thematic structure [productive resource] supports integration of key ideas in thermodynamics.	transferred from hot water to cold water but nothing from cold water to hot water. Student giving explanation of heat as condition of being hot to then half-way through the course elaborate on how phase transition relate to chemical bonds and transfer of heat.

3.2.8 Barriers to learning thermodynamics

The kind of guidance provided in the research by Robertson et al. (2019) could be a way of avoiding the overreliance of one equation or principle in physics. Multiple studies in PER deal with these kinds of barriers (e.g. Driver & Warrington, 1985; Geller & Daane, 2019; Loverude et al., 2002; Nordine et al., 2019) without explicitly referring to them as such. For example, in a study by Clough & Driver (1985), they interview students about conduction of heat and notice that a strong factor affecting the students reasoning seems to be that "heat rises": In one interview, they ask a student why a metal spoon would feel hotter than spoons of other materials when all of the spoons stand up in a jug of hot water. The student applies "heat rises" and states that the spoon heats up faster than it would be if it were heated from the side and argues that it is what they were told in science class. Here is a kind of *heuristic* (D. Kahneman et al., 1974) that the authors claim to be almost universally known by children which seems to be acting as a barrier in learning about types of heat transfer, and which the students claim to have learnt at school rather than from some everyday intuition. In this case, the barrier is a resource (potentially a heuristic (D. Kahneman et al., 1974)) that inhibits other resources that may have been productive for the reasoning process.

Another type of barrier seems to be of the contextual type, for example observable features distracting students' reasoning and potential application of an energy analysis in which energy is conserved (Driver & Warrington, 1985). A summary of the publications that include findings on obstacles and barriers in learning thermodynamics can be found in *Table 3* (at the end of *3.2.8*).

It is well-established, in education research concerning thermodynamics and thermal phenomena, that many learners have difficulties with concepts such as temperature, energy and heat (e.g. Brookes & Etkina, 2015; Erickson, 1979; Frederik et al., 1999; Kesidou & Duit, 1993; Warren, 1972) and that they, for example, tend to view temperature as the unit for heat (Greenbowe & Meltzer, 2003) or equate heat with temperature (Erickson, 1979). In everyday language, we say that a wooden ladle is "warmer" than a metal ladle at room temperature, even though it is really is about the thermal conductivity, density and specific heat capacity (through the function of thermal inertia) of the two different materials (Bohren, 2017). It is confusing that two objects with the same temperature but different thermal conductivity may be identified as "warm" and "cold" which then, as sense of touch is used as a thermometer, leads to the conclusion that the objects have different temperatures, see for example Schönborn, Haglund & Xie (2014). This seems to indicate that the sense of touch is a barrier in distinguishing temperature and heat, but that is not always the case as, for example, Carlton (2000) shows that it may be a productive resource for heat transfer if it is used as a starting point for teaching about heat.

A study by Frederik et al. (1999) suggests that some of the difficulties with understanding the relation between heat and temperature may be because of the association between heat transfer and temperature increase (e.g. *"heat transfer leads to temperature increase"* as a barrier) rather than heat transfer and phase transition: Heating water to above its boiling point for a certain pressure makes the water boil. Boiling, just like evaporation and melting, is however a cooling process: Energy is required for the phase transition. If the surrounding pressure is sufficiently reduced, by for example a vacuum pump, it is even possible to attain a temperature low enough for an amount of water to freeze and boil at the same time (for example (Hewitt, 2015, p. 353)).

Duit (1981) and Driver & Warrington (1985) have shown that the concept of *work* may hinder students in applying an analysis which involves energy transfer such as heating. Other researchers (Carlton, 2000; Taber, 2000) have suggested that teachers wait with introducing work together with concepts such as heat and temperature until when they have come to appreciate the latter concepts. In contrast to Carlton (2000) and Taber (2000), Loverude et al. (2002) argue that students should be taught the concept of work thoroughly in mechanics before even being introduced to thermal physics as the concept is needed (it is a productive resource) in learning about thermal physics.

Loverude et al. (2002) and Leinonen (2013) have shown how the *ideal gas law* can act as a barrier in using the first law of thermodynamics to problems involving adiabatic processes. Even after the instructor explicit mentioned the concept of work to students in the first study, the students did not apply the first law of thermodynamics to the problem. A potential reason for this may be found in a study by Rozier and Viennot (1990) that shows that students tend to apply *linear causal reasoning* to complex processes such as adiabatic compression of a perfect gas. The ideal gas law has also been shown to act as a barrier in understanding vapor pressure (Azizoglu, Alkan, & Geban, 2006). These results can be summarized as barriers in reasoning about energy. Other results in this category include the *substance metaphor* as an barrier in learning about heat as a process (e.g. D. Brookes et al., 2005; D. T. Brookes & Etkina, 2015).

So to summarize this part of the literature review: To distinguish heat and temperature is important in thermodynamics but it has also been shown to be a challenge for students as they rely on what they see and experience. Past *experiences* and *senses* are important when trying to understand phenomena in physics, and to some extent, chemistry. Another aspect affecting learners reasoning process is the *context* of a problem or phenomena: a student may *frame* a problem differently if a the context is changed. There are ways to take these aspects into account when designing a teaching sequence, for example by basing problems or phenomena on everyday situations and by supporting the students reasoning process by relating science to past experience. The next part in the literature review will cover a tool that may leverage some of these aspects in learning about heat.

Table 3. Barriers in reasoning about energy.

Publication	**Summary**	**Example**
(Driver & Warrington, 1985)	*Observable features* as barrier to energy conservation/energy analysis.	When responding on how to get weights, lifted by a water turbine, to be lifted faster, a student reasons that it could be higher up, and another student responds that the blades could be made larger.
(Clough & Driver, 1985)	*Observable features* as barrier to understanding heat conductivity *"Heat rises"* [potentially a heuristic or p-prim] as barrier to heat transfer.	Color and smoothness of objects as determinants of heat conductivity. Students arguing that a metal spoon becomes warmer when standing in warm water because "heat rises".
(D. T. Brookes & Etkina, 2015)	*Ideal gas law* act as a barrier in understanding heat as a process. The *substance metaphor* may act as a barrier in understanding heat as a process.	Weights are put on top of a piston in a cylinder, pushing down on an ideal gas within the cylinder. The cylinder is covered with a jacket filled with water and the entire system is at room temperature initially. Students are asked if there is a net energy flow between the water and gas when the weights are added to the piston and if so, from gas to water or vice versa. A majority of the students responding that there would not be a net flow applied the substance metaphor. Students using

		the substance metaphor all tried to apply the ideal gas law to the problem (no change in T
(D. Brookes et al., 2005)	*The substance metaphor* may act as a barrier in understanding heat as a process.	Students being asked questions about processes occurring in a cylinder, with a moveable piston, containing an ideal gas. The student's arguments included that temperature is a measurement of the amount of heat being present in a system which is described as a container of heat.
(Leinonen, Räsänen, Asikainen, & Hirvonen, 2009)	I*deal gas law* acts as a barrier to the first law of thermodynamics.	Student explaining what happens to the temperature in a task, which involved adiabatic compression, applies the ideal gas law. As it requires students to come to a conclusion that temperature and internal energy is increased in the process, they need some basic understanding of the first law of thermodynamics (work is done on the gas as $Q = 0$) to describe how it is increased.
(Loverude et al., 2002)	I*deal gas law* acts as a barrier to the first law of thermodynamics.	Student responding to whether pressure, temperature and volume of an ideal gas will increase, decrease or remain the same in an insulated cylinder with piston which a large number of masses are added to. Student responding that a decrease in volume lead to increase in pressure which increases the temperature according to $PV = nRT$. Students answer is insufficient as it does not tell us anything about the temperature change. First law of thermodynamics is needed (positive W lead to positive increase in internal energy and thus increase in temperature for adiabatic process).
(Rozier & Viennot, 1990)	Reducing variables/*linear causal reasoning* as a barrier to	In explaining why pressure increases for adiabatic compression of a perfect gas a student responds that volume decreases lead to molecules being closer and thus more

	understanding complex phenomena.	collisions which lead to an increase in pressure. A correct explanation is not linear (V decreases lead to increase in particles/V and mean speed of particles, therefore number of collisions per volume increases and mean speed of particles increases lead to increase in pressure).
(Chi et al., 1981)	*Literal features* as obstacles to core ideas in problem solving	Student categorizing a problem on energy conservation based on what is observable in the problem: blocks and inclined planes (experts categorized it as an energy conservation problem)
(Geller & Daane, 2019)	Resources supporting understanding of *energy conservation* may act as barriers to understanding free energy or energy degradation	Student struggled to reconcile an equilibrium situation where energy is distributed in a system, with the idea of energy conservation. Usefulness for the student was attached to each "bit" of energy rather than the distribution.
(Johnstone et al., 1977)	*"Higher to lower"* [potential heuristic or p-prim] act as obstacle in understanding that endothermic reaction can be spontaneous.	No qualitative example is given. A potential reason for students problem with spontaneous endothermic reactions is given: there is a "universal rule that situations tend spontaneously to a position of lower energy."(Johnstone et al., 1977, p. 248)
(M. C. Linn & Songer, 1991)	*Superficial models ("heat as fire")* as barriers to abstract models. Pragmatic model as solution (if students are motivated to use it).	When asked about the difference between temperature and heat, an example of a response from a student relying on a superficial model would be that heat is like a fire of which the hotness is measured as temperature. Pragmatic model offered: qualitative heat-flow model.
(Wittmann et al., 2019)	*"Air"* in a problem as a barrier to energy conservation.	Students tended to reply with answers that are based on the assumption that energy gets used up when "air" was included in problems on energy conservation.

(Kesidou & Duit, 1993)	A *"naïve" particle model* may act as an barrier to understanding the second law of thermodynamics	In applying the naïve particle model to a problem students conclude that particles slow down, and eventually stop, by themselves and so the energy is not conserved (it is used up) as new energy needs to be added to the system to keep the particles moving. Thus, there is no basis for considering energy distribution and the second law of thermodynamics.
(Frederik et al., 1999)	*Heating lead to rise in temperature* [potential heuristic or p-prim] as barrier to heat transfer and temperature in relation to phase transitions.	Participants frequently had the conception that heating always lead to an increase in the temperature. This made them relate heating to rise in temperature but not phase transitions in discussions (it made them "miss" relating the two concepts).
(Kesidou & Duit, 1993)	*"Sum is conserved"* [potentially a heuristic or p-prim] as barrier.	Students arguing that two bodies of different temperature have to have the same sum of temperature after a change in temperature of the two bodies (e.g. two bodies of 20 ^{0}C and 80 ^{0}C will always have a sum of 100 ^{0}C).

3.2.8 My research and "thermodynamics education"

From a physics content point-of-view, few studies have studied students' understanding of *phase transitions* in relation to the energy concept in terms of heating. The same is true of *hygroscopy* and *deliquescence*.

Phase transitions are one type of phenomena in which it is important to be able to distinguish temperature and heat and have a good understanding of the second law of thermodynamics. Much of the research in *Table 1* points at the fact that contexts are important in learning about heat, energy and related concepts. This is sometimes related to how learners frame a situation and thus apply different resources in different contexts.

Other research, see *Table 3*, shows that some resources, even the ones that in a traditional sense would be considered "correct" knowledge, such as the ideal gas law, may act as *barriers* to potentially *productive resources* in reasoning processes, or as distractors. The concept of barriers in meaning-making has not yet been related to the Resources framework and Social semiotics (or been theorized at all). My research aims at doing this. Another contribution in my research is of a theoretical sort: relating the Resources framework to the framework of Social semiotics, as framed by Airey & Linder (2017) through *resources*, *semiotic resources* and *framing* (*epistemological* and *conceptual framing*, e.g. what participants do and what knowledge they employ in a situation).

In addition, my research also adds to the growing list of research on *teacher education* (e.g. Daane, Vokos, et al., 2014; Frederik et al., 1999; Geller & Daane, 2019; Robertson et al., 2019) related to physics and research on physics perspectives on *chemistry education* (e.g. Corni & Michelini, 2006; Donaldson et al., 2019; Dreyfus, Gouvea, et al., 2014; Geller et al., 2013) with an emphasis on *thermodynamics* and the energy concept.

3.3 Technology for visualizing natural phenomena

3.3.1 Dynamic visualizations, simulations and MBLs

Linn (2003) reviews research on technology and science education from the late 1970s and onward: Early on, technology was adapted for traditional teaching. As computers got more powerful and researchers learned more about learning, the technology tested in science education was refined towards the needs of the learners rather than the established methods used by the teacher in the classroom. The *customization* towards specific types of difficulties students' have with learning science led to the development of for example visualization technology such as *simulations of heat flow* supporting the understanding of heat and understanding of graphing.

In a paper comparing simulations and laboratory equipment, Finkelstein et al. (2005) show how a *customized* and properly designed *simulation* of an electrical circuit, explicitly modelling the flow of electrons, may support learning better than real laboratory practice, both in learning the actual practice and conceptually. However, the authors do add that the result is context-dependent and should be viewed in the light of the learning environment in which it was tested. The success in using the simulation may be explained through the work of Papert (1980), more specifically through his concept of *microworlds*: To allow for experience of counterintuitive laws or principles in physics, one could design a microworld, for example a simulation, in which the physical principle is forefronted and *anchored* (Clement, 1993) in intution. As an example, "students have had almost no direct experience of pure Newtonian motion" (Papert, 1980, p. 123) which makes Newtonian laws of motion difficult to grasp for students: When you push a table it moves, when you stop pushing the table it stops. There are, however, instances where something that is pushed continues to move, like someone on ice-skates. Through a simulation, the student can experience even more instances of these kinds of situations as one, for example, could remove friction or gravitational force thus designing a microworld where Newtonian motion is intuitive. This idea has later been adapted in PER in open-ended digital environments such as Algodoo (Euler, 2019).

More recently, compared to the works of Papert, through a meta-analysis, McElhaney et al. (2015) review papers on *dynamic visualizations*, such as simulations, in science education from year 2000 and onward, and come to the conclusion that it is common for research on dynamic visualization to be designed as short laboratory tasks that involve a single concept rather than more complex phenomena such as phase transition. In addition, McElhaney et al. (2015) present aspects of visualizations that have been shown to support the learning of science content:

- Using an informal or *personal tone* in instruction seems to make content more accessible and relevant for learners.
- *Visual cues* to distinguish relevant from irrelevant information. However, they also add that this is a trade-off as too much help may lead to the activity becoming a step-by-step instruction, which in turn is shown to have very little effect on learning with dynamic visualizations.
- *Sequential conceptual representation* in which parts of a representation is shown in succession, has a much higher effect on learning than simultaneous conceptual representation (which has small negative effect on learning). Some of the reviewed research does however show that this depend on the prior knowledge of the learners: high prior knowledge learners benefitted from *simultaneous conceptual representation* as they managed to link the parts of the representation into a single unit while it was a too high cognitive demand to do so for low prior knowledge learners.
- *Static images*, like snapshots of an animation, seem to inhibit sense-making in collaborative learning (however, they are marginally effective for individual learners).
- *Interactive features* of dynamic visualization encourages inquiry learning.
- The *degree of control* of interactive features is suggested to be highly context-dependent as, while giving students control over many variables seem to be detrimental for learning compared to fixed values of the same variables, few controllable variables may be beneficial for learning.
- *Prompts* that require students to distinguish between time-points or elements in the visualization are shown to have a large positive effect on learning. Such prompts could for example be the task for students in giving feedback on each other's animations of chemical reactions or the task of finding the relevant aspects of a dynamic visualization

of honeybee communication. Scripted instructions such as explicit heuristics are shown to have the least positive effects on learning.
- Studies on *3D information* in dynamic visualizations are shown to have no apparent pattern in being beneficial or detrimental to learning.

A type of device developed within PER called MBLs (Microcomputer-Based Laboratory) involves dynamic visualizations and was a result of a project at Technical Education Research Centers (Sokoloff et al., 2007). In this project, devices with built in sensor for collecting real-time data were developed (the MBLs). In 1992, Sokoloff, Laws and Thornton (2007) integrated the MBLs in a curriculum which they called *RealTime Physics* (One of its four modules is on thermodynamics). RealTime Physics has four goals:

> *(1) acquire an understanding of a set of related physics concepts; (2) experience the physical world directly by using MBL tools for real-time data collection, display and analysis; (3) develop traditional laboratory skills and (4) master topics covered in lectures and readings using a combination of conceptual activities and quantitative experiments.*
> (Sokoloff et al., 2007, p. 85).

Beichner (2009) describes some of the early research on technology in PER. He suggests that the early work on *microcomputer-based labs (MBL)* led up to the specialized studies of today's PER, so MBLs may be a good basis for a literature review on educational technology, as research on educational technology is a quite broad topic. I have limited my literature review to mainly *infrared (IR) cameras* (see *3.3.2*), which could be considered a type of MBL-device in that it shares features with MBLs, e.g. it can be moved around within the environment and be used to collect data on infrared radiation to display thermal images of the environment.

Bernhard (2018) argues that, in education research, technology has often been perceived as objects of low cognitive value, that is, they are to be used to gather some kind of knowledge but the actual use of the tool itself, that is the meaning-making, is not studied. In his study, Bernhard (2018) shows that the cognitive value of a technology may differ from technology to technology. Thus, it is important in research to also consider and study the learning potential, or *pedagogical affordances*, of a technology through, by, for example analyzing how a technology is used during a learning process, as "you learn to see through a microscope by doing, not just by looking" (Hacking, 1983, p. 189).

The use of technology, in terms of the ways the tool communicate some meaning, has been a focus of research in PER using a Multimodal and/or Social semiotic perspective (e.g. Airey & Linder, 2017; Jewitt, Bezemer, &

O'Halloran, 2016). For example, Volkwyn et al. (2019) describe how, in general, the meaning of the sign is *flexible* as individuals make and interpret the signs. However, for a community or discipline like physics, the meaning making between device and individual is far more constrained than between individuals in general, as the physics community has decided on what information is relevant and how it should be interpreted. In a way, the device maker has the interest of the physics community in mind when designing it. Airey & Linder (2009) suggest that it is possible to leverage this device making in teaching and learning physics, as it is possible to view the device as a *condensation of meaning*. If one gains access to the development of the device one also gains access to the ways of knowing brought into the development of it. Thus, as is suggested by for example Airey & Eriksson (2019), and Paper I, it should be possible for a semiotic resource in physics to have both disciplinary and pedagogical affordance. In other words, a device used for some purpose by experts in a discipline, for example physicists, could also be relevant for support in teaching the discipline to students in physics.

In a study by Scaife & Roger (1996), they review previous research on how *representations* (static diagrams, animations and virtual reality) can support learning and find that there are three aspects of support: *computational off-loading*, *re-representation* and *graphical constraining*. A device using any of these representations would therefore be a candidate of pedagogical affordance through some of these aspects, for example by giving the students a focus on the relevant aspects of a phenomenon. In line with this, Volkwyn et al. (2019) suggests that physics devices can fulfil three different functions: *intensifying*, *filtering* and *transduction* of which the filter function acts like the constraining aspect proposed by Scaife & Roger (1996) or as how learners can benefit from visual cues in dynamic visualizations by distinguishing relevant from irrelevant information (McElhaney et al., 2015). A device may also act as a filter for irrelevant aspects in the environment like how Kluge (2019) shows that a simulation of a heat pump acts as a *focal point* for students' talk or Atkins et al. (2009) and Jeppsson, Frejd & Lundmark (2017), that show that IR cameras can direct the attention of learners to the task at hand.

Some combinations of semiotic resources, for example touch, speech and visualization, seem to improve learning in some cases (Clark & Jorde, 2004), but not in others (Schönborn et al., 2014). This could be a result of students participating in the latter study not being fluent in one, or more, of the *semiotic resources* thus lacking the *fluency in a critical constellation* (Airey, 2009; Airey & Linder, 2009) of semiotic resources necessary to understand the task at hand. For example, in the study of Schönborn, Haglund & Xie (2014), the researchers found that the students could not reconcile their observations with their prior knowledge and that they tended to use IR cameras as a thermometer. Through a Social semiotic lens, the students were not fluent with the semiotic resources of the technology as they did not seem to take advantage of the spatial affordance of thermal imagery.

3.3.2 Infrared (IR) cameras

Over 200 years ago, William Herschel discovered infrared radiation when he placed a thermometer in the visible range of the solar spectrum displayed on a table. He then moved the thermometer across the spectrum toward the red end of the visible range. Perhaps out of curiosity, he continued by moving the thermometer outside of the visible range and noticed that the temperature increased even more outside of the red end. Thus, through his observations, he had discovered *infrared radiation*, which is what infrared (IR) cameras are based around.

What has later been discovered is that all objects above 0 K emit thermal radiation. IR cameras are based around this fact and that many objects that we encounter in our everyday life emit radiation in the infrared range of the spectrum (3-15 μm). An IR camera has a lens made of material transparent in IR, for example germanium, and is thus able to detect direct emission of thermal radiation.

Theoretically, it is possible to find a thermal radiation spectrum, through Planck's law, for blackbodies but for real cases this has to be modified by the emissivity, ϵ, of a body as a blackbody is an idealization (Vollmer, Möllmann, Pinno, & Karstädt, 2001). A value for the emissivity of the surfaces one wants to observe with an IR cameras thus has to be chosen for the IR camera by the user. A common choice for this, which I have used for my IR cameras, is 0.95, close to the value of for example water, wood, silicon carbide, plastics and many paints. The IR camera gives the wrong readings of "shiny" surfaces, if one choose an emissivity of 0.95, as they usually have a much lower emissivity (alumium has an emissivity value that is lower than 0.1 (Ludwig & Carpineti, 2020)). A temperature is calculated and displayed by the IR camera for the point which the hair cross points at. Other points in the image on the display of the IR cameras are given a color from a, by the user, chosen color scheme which represents the range of temperatures of the points in the view of the IR cameras (see Figure 3).

IR cameras have been used in many areas of research and development, for example in the development of toys monitoring physiological aspects of children with disabilities (Murphy et al., 2015) and in the research on volcanic activity (Sawyer & Burton, 2006). A growing field of research is how to apply IR cameras in education, especially physics, engineering and chemistry (Vollmer et al., 2001; Xie, 2011; Xie & Hazzard, 2011). In the light of previously mentioned research on visualization and learning technologies, IR cameras can be said to be a dynamic visualization technology but does not completely fulfil the description of an MBL. A more extensive explanation of the technology can be found in a publication of Vollmer & Möllmann (2010) in which they outline the theory and applications of IR cameras.

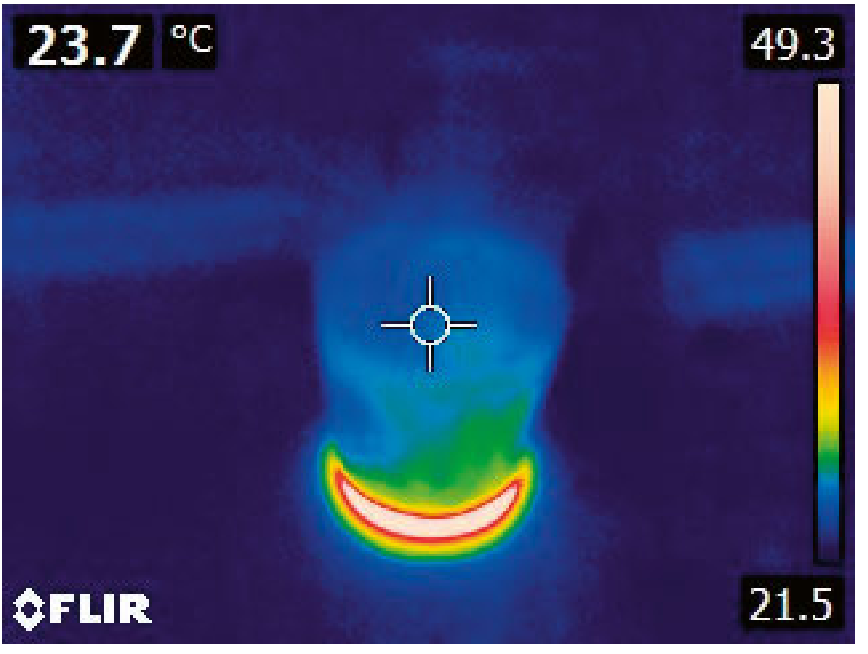

Figure 3. Thermal image, of an exothermic reaction (sodium hydroxide in water) in a plastic cup, generated by an IR camera. The value in the upper left corner indicate temperature of the point which the hair-cross is directed at. The range to the right give the maximum and minimum temperatures of the image in addition to an indication of what temperature range the colors translate into.

Observations are central in the design of IR cameras and important for the progress of science but to know what aspects to attend to in an observation requires practice. For example, Herschel's sister, Caroline Herschel was great at discovering comets[14]. She used a device to scan the night sky for objects and a telescope to get a better look at the objects when she suspected an object to be a comet. However, as Hacking (1983, p. 180) describes it "But the most important of all, she could recognize a comet at once. Everyone except possibly her brother William had to follow the path of the suspected comet before reaching any opinion on its nature".

Goodhew et al. (2015) outline four psychological principles that guide successful visualization, one of which touches upon the topic of *attention*: attracting the attention toward a certain aspect can be done by shifting something invisible to becoming visible (the novelty in what is seen attracts the attention). The information that is provided through the visualization should then be personally relevant, provide link between the potential problem investigated and the solution, and be specific rather than general. Thermal imaging could be suggested to fulfill these four principles and thus provide support in

[14] Hacking (1983) claims that she discovered eight comets in a year.

students' learning process. In the study, Goodhew et al. (2015) explored how thermal images affect house owners' behavior in terms of actions taken to save energy. The results of their study show that exposure of thermal imaging can change the behavior of those who view the images in terms of energy saving actions. For example, people who had seen thermal images of their homes were "nearly 5 times more likely to draught proof their homes than those not exposed to thermal images" (Goodhew et al., 2015, p. 1083).

The topic exploring this potential for support in learning has been investigated by several researcher for the last two decades. Two strands of papers can be found on the topic (see Table 4): *Experiments* involving IR cameras that are re-formulated into lab activities to use in physics education and *empirical studies* on students' use of the tool and if it supports understanding of concepts such as heat and temperature.

Table 4. The two types of studies on infrared cameras in education.

Description	**Source**
Lab activities involving IR cameras (and technology of IR cameras)	(Xie & Hazzard, 2011) (Xie, 2011) (Short, 2012) (Melander, Haglund, Weiszflog, & Andersson, 2016) (Kácovský, 2018) (Netzell, Jeppsson, Haglund, & Schönborn, 2017) (Wong & Subramaniam, 2018) (Xu, Wu, & Wang, 2019) (Vollmer & Möllmann, 2018) (Palmerius & Schönborn, 2016) (Haglund & Schönborn, 2019) (Vollmer et al., 2001) (Vollmer & Möllmann, 2012) (Xie, 2012) (Kubsch, Nordine, & Hadinek, 2017) (Möllmann & Vollmer, 2007) (Vollmer & Möllmann, 2013) (Green et al., 2020) (Bohrmann-Linde & Kleefeld, 2019) (Kácovský, 2019) (Ayrinhac, 2014) (Ludwig & Carpineti, 2020)

Empirical, and *theory-based* studies on students use and learning with IR cameras	(Haglund, Jeppsson, Hedberg, et al., 2015) (Schönborn et al., 2014) (Haglund, Jeppsson, & Hedberg, 2015) (Haglund et al., 2017) (Dolo et al., 2018) (Jeppsson et al., 2017) (Haglund, Jeppsson, Melander, Pendrill, & Xie, 2016) (Atkins et al., 2009) (A. Larsson, Stafstedt, & Schönborn, 2019) (Nordine & Wessnigk, 2016) (J. Goodhew et al., 2015) (Steg, 2016) (Boomsma, Goodhew, Goodhew, & Pahl, 2016)

Vollmer et al. (2001) proposed ways of integrating IR cameras in physics education to teach topics such as mechanics, optics and thermal physics. It was followed by other papers giving more suggestions on how to implement the technology in education (e.g. Möllmann & Vollmer, 2007) but also by an empirical study (Atkins et al., 2009) in which visitors at a science museum were invited to investigate insulating properties of clothing in a semi-structured way. Labels with suggestions and questions were placed together with the clothing that the visitors could investigate. The researchers noticed that the visitors seemed to frame the activity as a lesson and that, by using the IR cameras, they gained a focus on talking about and exploring heat and temperature.

Vollmer & Möllmann (2010) later collected many of the experiments and scientific explanations in a book. Additional papers have been published after this on activities involving IR cameras. These include activities such as seeing the temperature increase from latent heat released through condensation when a paper is put on top of a glass of water (Xie & Hazzard, 2011), observing the temperature decrease of fire extinguishers to illustrate the adiabatic expansion of a gas (Joule-Thomson throttling) (Melander et al., 2016), measuring the surface temperature of the moon (Vollmer & Möllmann, 2012), temperature change of components in an electric circuit (e.g. Ayrinhac, 2014; Kácovský, 2019) and evaporative cooling of water and ethanol on strips of paper (Kácovský, 2018).

More recently, empirical studies have been conducted involving students using IR cameras to learn more about thermal phenomena such as how the emissivity of a surface relates to the readings of a camera (Haglund et al., 2017): low emissivity surfaces, such as shiny metals, will give inaccurate temperature readings as the IR camera usually is set on an emissivity close to 0.95 which gives accurate readings of materials like wood and plastics. From the empirical studies (Haglund, Jeppsson, & Hedberg, 2015; Haglund, Jeppsson, Hedberg, et al., 2015; Haglund, Jeppsson, Melander, et al., 2016; Haglund et al., 2017; Schönborn et al., 2014) it can be concluded that how students use IR cameras changes with the educational level and how experienced the students are with thermal science. A phenomenon (reflection of infrared light in low-emissivity surfaces) visible through the IR camera may be interpreted as a problem with the measurement by a group of students at high school level (Haglund, Jeppsson, Hedberg, et al., 2015) but is noticed and discussed as a physics phenomenon by students at university level (Haglund et al., 2017). Students in 7th grade have been found to use the IR cameras as thermometers and find it difficult to reconcile their observations of the temperatures of wood and metal being the same with their experience and prior knowledge of wood feeling "warmer" than metal (Schönborn et al., 2014). In line with Arnold & Millar (1996) and Linn & Songer (1991), Schönborn et al. (2014) propose that a *simple heat-flow model* is introduced to students before being presented with their teaching intervention (in this case with IR cameras). Haglund, Jeppsson & Hedberg (2015) have later tested this suggestion with a group of students in 4th grade. The students were presented with a model in which "heat tends to flow from warm objects to cold objects, with which they are in context, and that insulators may be used to hinder such heat flow" (Haglund, Jeppsson, & Hedberg, 2015, p. 426). It was found that many of these students, after being presented with a heat-flow model, were able to engage in *instant inquiry* of thermal phenomena with the IR cameras, propose their own experiments, and apply the taught heat-flow model on the presented phenomena (Haglund, Jeppsson, & Hedberg, 2015).

Giving students some time to first learn a model, or to discuss their initial ideas about the content to be taught, before introducing them to IR cameras is also suggested by Nordine & Wessnigk (2016). In their proposed and tested teaching sequence for middle school students, students are to first discuss their ideas about energy to then experience and discuss some phenomena involving energy transfer and transformation without using IR cameras. The IR cameras are first introduced in the third stage of the sequence, in which the students are to freely explore their surroundings before turning to the tasks designed by the researchers. Some initial results in the study show that students participating in this sequence have begun developing an understanding of thermal equilibrium and heat transfer.

Others have followed the suggestion of Schönborn, Haglund & Xie (2014) more directly by introducing a heat-flow model before letting students use IR cameras to support their learning: In a study by Larsson, Stafstedt & Schönborn (2019), 4th grade students visiting a science center get to engage in investigating thermal phenomena with IR cameras. However, before they get to use the cameras, the researchers present the students with a simple heat-flow model. The result shows that the students engage in exploring a multitude of different thermal phenomena and that they combine and shift between different metonyms and metaphors in explaining their observations. It is also shown that the students compare and contrast observations made by their bodies, through touch of surface, with the observations made through the cameras. In addition, movement seem to be central to the conceptualization of heat for the participants. This may be a problem in situations where change is not visible. For example, Kubsch, Nordine & Hadinek (2017) suggest that the association between energy and movement may lead to problems for students in interpreting situations that appear static but involve "hidden" energy transfers, such as when sitting in the "wall seat" position. IR cameras are able to visualize the result of the hidden energy transfers as temperature increase in the skin of the legs and could thus be used to resolve problems with the interpretation of what appears to be static activities.

3.5 Situating my own research

Following the overview of Docktor & Mestre (2014) in PER, I will here return to their overview of PER and elaborate on each of the topics presented in their paper (see *Table 5*): the relevance of each topic in relation to my research and to my review of research on the learning of thermodynamics, technology for visualizing natural phenomena and learning and social interaction.

Each point of relevance will be elaborated on following *Table 5*. Included in the table are the outcomes and frameworks found in the review by Docktor & Mestre (2014). However, the frameworks and outcomes are sometimes relabeled by me to make the summary easier to read. For example, Docktor & Mestre (2014) list aspects that influence the theoretical framework of cognitive psychology which I have summarized as *Cognitive science* (each aspect is framed by the framework sometimes referred to as human information processing as part of the discipline of cognitive science). These aspects do not really define a theoretical framework on their own which is why I instead choose to refer to them as information processing in the table.

Table 5. Topics in general PER as formulated by Docktor & Mestre (2014) related to the review of research on thermodynamics education.

Topic	**Outcomes of the research**	**Frameworks**	**Relevance**
Attitudes and beliefs about teaching and learning	Students attitudes and beliefs Faculty beliefs and values Instructor implementations of reformed curricula Teaching assistants	Student attitudes and beliefs Instructional practices and conceptions	Coherence and reality
Problem solving	Expert-novice Worked examples Representations Mathematics Instructional strategies	Information-processing Analogy Resources Situated cognition	Surface attributes vs. principles Quality of information Representation format
Cognitive psychology	Knowledge and memory Attention Reasoning and problem solving Learning	Information processing	Framing, context and attention Knowledge organization Language
Assessment	Concept inventories (CI) Comparing CI with other measure Comparing CI between populations Course exams and homework Rubrics for process assessment Complex models of student learning	Quantitative measurement in education Reliability and validity	Context and questions

Conceptual understanding	Misconceptions Architecture Instructions	Misconceptions Knowledge in Pieces/Resources Ontological categories	The resources architecture
Curriculum and instruction	Lecture-based Recitation or discussion Laboratory	Constructivism (and associated frameworks)	Peers MBL Authentic practice

I will elaborate on each of the findings reviewed by Docktor & Mestre (2014) that are categorized as relevant to my research and relate it to some of the studies described in my literature review:

- *Coherence and reality* – A measure of students' epistemological beliefs or attitudes. *Coherence* refers to the view of a student in how physics is structured. High coherence, or favorable coherence as the authors refer to it is when students view physics "as a connected system that is relevant to every experiences oin the real world"(Docktor & Mestre, 2014, p. 37). Low coherence, or unfavorable coherence, is the view that physics consists of unrelated pieces of information. In the same vein, *Reality*, referred to as *Reality link* or *Real-life applicability* in the overview of Docktor & Mestre (2014), relates to whether students think of physics as relevant to reality and everyday situations. Favorable shifts of students' epistemological beliefs have been shown (Elby, 2001; Hammer, Elby, Hammer, & Elby, 2009) to be linked to instructional practices where students think about their thinking, for example by reflecting on the strategies used to learn about physics or arguing against and for a multitude of different perspectives on a topic. In social interaction, the latter practice may potentially be expressed as exploratory talk (Mercer, 1995) in which the ideas of a group of students are critically and constructively evaluated and as such trained in arguing for and against certain statements or suggestions. Kluge (2019) shows how the progress of a discussion in a group is done by some of the participants by them testing their awareness against the other participants of the group: For example by actively pointing out how pressure affect a simulation of a heat pump, a student tests if the aspect he is attending to could be argued to explain a phase transition. Another potential way to achieve favorable shifts of students epistemological beliefs, in terms of coherence and reality link, which may allow students reconciling the real world with science (Wiser & Amin, 2001), is to subject students to problems based on real-world situations, especially at the beginning of the teaching as suggested by Duit & Neumann (2014).

- *Surface attributes vs principles* – Novices tend to attend to surface features in problems in contrast to more experienced problem solvers, labeled experts in the review of Docktor & Mestre (2014), who instead categorize the problem and apply principles and concepts according to the category. Similar results are shown in research on thermodynamics education as shown in the category of contexts in *Table 1*. This is also in line with the idea that when learning something new, or forming new categories, the learner tends to attend to salient features or stimuli, as a novel category usually is related to characteristics that are exemplary to us (Rosch, 1973), e.g. what we see or sense.
- *Quality of information* – Experts structure the available information in a problem to then assess the quality of the information before trying to solve the problem. This could be an explanation to why students making their readouts of a phenomenon explicit are better at explaining the phenomenon than those who do not (Kluge, 2019). The students are acting in an "expert-like" way. As such, exploratory talk (Mercer, 1995), in which information is shared and scrutinized, could signify a more expert-like way of reasoning.
- *Representation format* – The way a problem is represented affects students' performance in solving the problem. Neumann et al. (2013) show similar effects of how the structure of a problem, in their case the context of the problem, affect students' problem solving. As such, this relates to the contextual category of studies in thermodynamics education (see *Table 1*).
- *Framing, context and attention* – As described in the literature review on contexts in 3.2 Learning of thermodynamics, what knowledge gets activated when and for what purpose depends on how one frames a situation: what meaning one makes of a context and what features or aspects that one pays attention to in that context. Cognitive resources supporting understanding of energy conservation may be applied by a learner in a situation framed to be about energy even though the resource for that specific situation may be unproductive, for example in understanding free energy (Geller & Daane, 2019). An everyday context of a phenomenon may make researchers and teachers in a discipline ("experts") apply everyday knowledge in attempting to explain the phenomenon (Lewis & Linn, 2003). In addition, a problem on energy transfer and transformation mentioning air (even though it is not relevant for the task) may be framed by students as if air specifically was relevant even though it is not (Wittmann et al., 2019). Focusing on air as a relevant aspect in a task while associating air to heat and cold (Erickson, 1979) may lead to students employing cognitive resources related to heat and cold when encountering contexts in

which air is foregrounded. However, Wittmann et al. (2019) show that including "air" in a task can inhibit the response that energy transfers from an object (a pendulum) to the air (energy is instead thought of as being "used up").

- *Knowledge organization* – Experts' knowledge is usually structured as clusters of chunks of associated knowledge. These clusters also contain procedural knowledge and the conditions for when applying the cluster. In contrast, novices tend to apply units of information (one equation or concept) in their reasoning. The difference of organizations is similar to the descriptions made by Chi, Feltovich and Glaser (1981) where experts categorize problems according to some core ideas and novices rely on literal features of a problem. The simple organization of students may cause the obstacles for students described in 3.2 Learning of thermodynamics, for example linear causal reasoning in reasoning about thermal phenomena (Arnold & Millar, 1996; Rozier & Viennot, 1991; Viennot, 1998) or overreliance on specific information units such as the ideal gas law (Leinonen et al., 2013; Loverude et al., 2002) or the concept of work (Driver & Warrington, 1985). However, this is not only a problem for students or novices but as Lewis & Linn (2003) have shown, experts may not always be able to switch to the knowledge needed in explaining a thermal phenomena, in terms of knowledge structure, they do not always have the right conditions for applying a specific cluster of knowledge to a context.
- *Language* – making the role of metaphors in science explicit in teaching supports students' learning process. This is in line with some of the reviewed research (Geller & Daane, 2019; Wittmann et al., 2017) in 3.2 Learning of thermodynamics. In contrast, some research advices against using the substance metaphor as it is reflected in common misconceptions held by students (Louisa, Veiga, Duarte, Pereira, & Maskill, 2007) or may act as an obstacle in reasoning about heat (D. T. Brookes & Etkina, 2015).
- *The resources architecture* – Students' knowledge is structured through fine-grained knowledge structures, often referred to as *resources*, that may be correct for some situations and contexts and incorrect for others, partly depending on how they are compiled. This is the foundation for the Resource framework which is one of the categories of thermodynamics education as structured in *Table 2*.
- *Peers* – Discussions among peers are potentially a fruitful base for conceptual development. Types of talk such as exploratory and cumulative talk (Mercer, 1995) relate to the actions carried out during laboratory practice (Andersson & Enghag, 2017) to learn about some content. Additionally, as shown by Beatty et al. (2006), discussions among peers in physics education stimulate students' cognitive skills such as reasoning as students have to share and test their ideas against

others' ideas. Questions can in turn be engineered, through tactics such as compare and contrast, and remove nonessentials, to direct focus of a discussion towards aspects relevant for the task at hand. Problem-Based Learning (PBL) is a method that has been successful (Duch, 1996, 1997) in leveraging students' discussions to teach critical thinking and communication of physics. The instructor's role in the method is to support discussions through probing questions while students solve real-world problems.

- *MBL* – As described in 3.3 Technology for visualizing natural phenomena, MBLs are tools used to visualize real-time data in the lab. An example of such a tool is the IOlab (a small box with many sensors) which has been shown to be useful part of in students' learning, about Earth's magnetic field, contributing to the critical constellation of semiotic resources affording the learning of the students (Volkwyn et al., 2019).
- *Authentic practice* – in line with NGSS, some methods, like Investigative Science Learning Environment (ISLE) (e.g. Etkina, Murthy, & Zou, 2006), aim at an authentic practice for the students, that is, engaging the students in the same way a scientist would be engaged in the laboratory. As argued by Robertson et al. (2019), teachers should to initially take students ideas seriously, formulate those ideas in hypotheses and test them through experiments, which is in line with an authentic practice such as ISLE.
- *Context and questions* – like research by Neumann et al. (2013) and Wittmann et al. (2019) shows, contexts of questions and problems affect how students respond. Docktor & Mestre (2014) refer to this as sensitivity to question context and describe the result of a study (Stewart et al., 2007) showing a similar contextual impact to students' responses.

Following the more recent trends of studying the learning of physics in disciplines or programs other than "standard physics" (bachelor and master in physics), the research presented in this thesis explores the learning of some physics content, or the possible enhancement of learning the content, in a chemistry course (Paper I) and a physics unit for middle school teacher students (Paper II).

When it comes to the concept of heat, Knight describes the learning objectives of thermodynamics to be "To begin to understand heat and the process of heat transfer. […] To understand two important consequences of heat transfer – temperature change and phase change" (Knight, 2004, p. 169). Additionally, added heat to a system can lead to an isothermal expansion. Temperature change and phase change relate to the physics content presented in the two papers for this thesis, namely hygroscopy and state of matter.

Very few papers in my review deal with phase transition, latent heat and hygroscopy. However, they all relate to some important difficulties that previous studies have shown that students have, for example distinguishing heat and temperature (e.g. Erickson, 1979; Warren, 1972) (which is necessary in understanding phase transitions) and heat transfer during forming or breaking of chemical bonds (e.g. Dreyfus, Sawtelle, et al., 2014).

In relation to this, as publications on IR cameras most often are on proposed activities, few papers (Haglund, Jeppsson, Hedberg, et al., 2015; A. Larsson et al., 2019) theorize about IR cameras as a tool to support the understanding of heat and temperature. I would argue that my research contributes to this part of PER.

3.5.1 Research questions

Against the background of the provided theoretical framework and literature review, and given naturalistic settings and phenomena[15], where participants investigate thermal phenomena that involve phase transitions and heat transfer with IR cameras within teaching units on thermodynamics, the thesis is guided by the following research questions:

RQ1: What are the affordances of the semiotic resources of the IR cameras, in undergraduate students' and instructors' investigation of thermal phenomena, in a teaching unit on thermodynamics, and how do the semiotic resources relate to the participants' framing and resources employed in their investigations?

RQ2: How do primary school teacher students, engineering students and instructors come to conceptually frame the situations that they are presented with for their investigations with IR cameras?

RQ3: How do primary school teacher students, engineering students and instructors come to epistemologically frame the situations that they are presented with for their investigations with IR cameras?

RQ4: How can resources support or hinder meaning-making and reasoning for undergraduate students and instructors investigating one or several thermal phenomena?

[15] I.e. settings that the participants would act in in their professions or education, and phenomena that they would encounter or use in their profession or education.

4. Assumptions from theory and literature review

The following chapter draws from the chapters on theory and literature review to filter out the aspects that inform the methodology for my studies as a set of *axioms* underpinning my research. I have formulated these aspects as *two categories of assumptions*: One category includes assumptions based on the results from the literature review and on the other the theoretical constructs from theoretical frameworks applied.

4.1 Assumptions based on themes found in the literature review

- **Framing and observable features:** Contexts are relevant to meaning-making. When encountering a situation or problem it is framed based on some cues or aspects that are associated to some earlier experience in addition to larger aspects such as culture and roles of participants. Observable features seem to be more accessible to learners in conceptual framing (e.g. in determining how to approach a problem in terms of what resources to employ), and for the reasoning process that follows.
- **Productive resources:** Some resources direct reasoning towards the target of the teaching and learning. These can be highly contextual depending on what each individual has experienced and associate with the situation in addition to what the final negotiated knowledge shared among the participants are. Other resources may be productive in that they focus or re-focus some reasoning on the aspects that lead up to the target of the teaching when discussions are wandering away from the topic at hand.
- **Barriers**: Resources may also act as barriers for some concepts or ways of knowing.
- **Technology & teaching material**: The inquiry type of use of IR cameras depend on the disciplinary experience of the users or scaffolding by providing some model or teaching material supporting the learners understanding of the disciplinary content of the investigated phenomena.

4.2 Assumptions based on theory

- When encountering and trying to understand a situation, we frame the situation based on some *semiotic resources*. The *framing* can be epistemological and conceptual. *Resources* inform how we interpret those aspects.
- Learning is the application of *resources* to *make meaning* of some content relevant to the discipline being taught, leading to new understandings.
- When learning, or meaning-making, leads towards an understanding that is relevant to the discipline being taught, it is said to be *productive*.
- Knowledge is conveyed through *semiotic systems* of which a specific type is referred to as a *semiotic resource* (e.g. red is a semiotic resource and colors is the semiotic system which red belongs to).
- The *function* of a semiotic resource, e.g. what *meaning it conveys* for one, or multiple participants, in a specific context indicate the *affordance* of the semiotic resource.
- That which is not directly visible in a situation is *appresented* but given enough experience with the situation or supported by semiotic resources with *pedagogical affordance*, a person may pay attention to what is appresented.
- The initial response (activation of some *resources* from which *framing* emerges) is made by the individual learner, which then is *negotiated* through discussions with peers (if available) to either lead to common and shared understanding or a set of understandings (if no agreement is reached).
- Talk, and other multimodal means external to an individuals cognition, give access to a person's or a group's knowledge structures. Discussions are not only useful for individuals to process their knowledge but also for the researcher in making the individuals knowledge explicit. In this research, a preferable method for collecting data is thus *video recording* as this enable an analysis of the full process of negotiation.
- How learners use a teaching material (the practice), such as an educational technology, infers something about the *affordance*s of the semiotic resources of the teaching material. If the use contributes to *productive meaning-making*, the affordance is said to be *pedagogical*. If the use also leads to providing access to *disciplinary relevant knowledge*, the affordance is said to be *disciplinary*.
- The practice, and thus use of teaching materials, may be analyzed through the *actions* and/or *type of talk* used by the participants (Mercer's (1995) typology of talks).

- Traditionally, research on the cognitive aspects of students learning have been carried out in laboratories or “artificial”, or *in vitro*, settings (in relation to the settings where the students are commonly taught). This produces outcomes for those settings that may not have been the outcomes in the naturalistic or authentic settings (*in vivo*), as it is not experienced as part of their regular education (Dunbar & Blanchette, 2001). This is why I have tried to conduct my interventions in connection with or within the students’ regular classes, always utilizing the same classroom or lab in which they just had their class/lab.

5. Methodology

5.1 Naturalistic inquiry

Research on education can be of two different types depending on the aim of the research: Just like how temperature as a concept only makes sense for a quantity of molecules rather than a single molecule, it makes more sense for some research in education to apply *quantitative methods* (e.g. comparing students' performance within two different curricula for a country through statistical analysis), thus generating results for a quantity of "molecules", and other to apply *qualitative methods* (e.g. through interviews and discourse analysis investigate how a specific group of students experience a specific topic within physics), generating results for one or a small group of "molecules". The quality of quantitative methods depends on the size of a data set (a large data set is preferable). In contrast, for a certain amount of time, a small data set typically yields a higher quality of qualitative analysis: Spending twenty hours on analyzing the talk of one student gives a more detailed analysis than if those twenty hours were spent on twenty students (given the same researchers in the two cases).

The two approaches should be thought of as complementing and informing each other rather than there being some sort of contradiction between the two. That being said, I have chosen to apply *interpretative qualitative methods* in the two papers in this thesis as that approach better serves in answering my research questions (involving the process of meaning-making). In terms of data collection, qualitative methods (e.g. interviews) are usually more time-consuming than quantitative which means that the amount of participants, generating the data, that can be included are rather limited[16]. However, returning to the analogy of particles, more time may be spent on each "molecule" of the data, which, although making the findings more *trustworthy* (Guba & Lincoln, 1982) on a small scale level, may be difficult to transfer to other, higher cultural or content-wise levels (e.g. transferring results upward in *Figure 4a*), such as education in the country in general or for learners in general.

Similar problems may be encountered when trying to transfer findings from a high cultural or content-wise level to a lower one (transferring down-

[16] Quantitative methods could potentially be applied to data generated by a single individual, for example by statistically analyzing speech markers such as pauses or words.

wards in *Figure 4a*): For example, transferring results about learning processes in general to the case of a student learning about friction in a Swedish high school. The results from the higher level may accurately describe the learning process at the lower level but it is more plausible that research on that specific student's learning process (same cultural level) or on learning processes on learning about friction (same content-wise level) are better at describing the suggested situation. Some suggested levels of data sizes are illustrated in *Figure 4.*

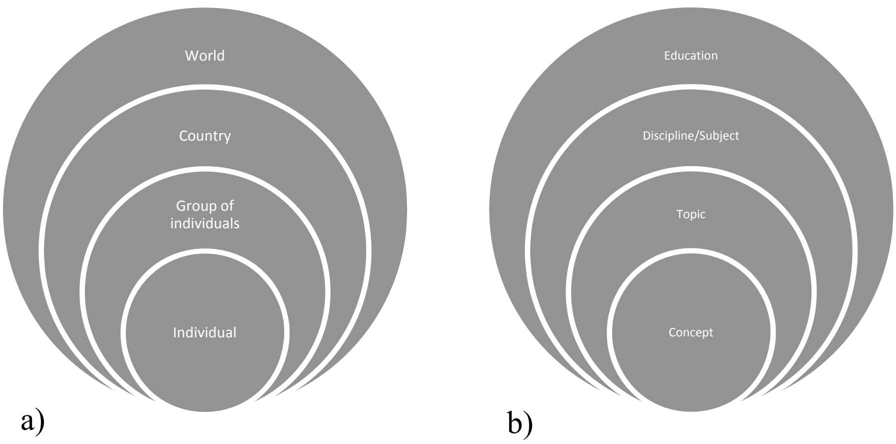

Figure 4. a) Levels of cultures, and b) Levels of content, that can be investigated in a study.

A physical phenomenon such as increasing the temperature of a piece of paper due to the latent heat released by water when condensing on the paper will always have the same result given the same conditions. It is thus appropriate to use a *rationalistic* or *scientific approach* to study the phenomenon: control the humidity of the room, temperature of the water evaporating and later condensing onto the paper, and the room temperature, to see if the experiment end with the same result for multiple attempts. Indeed, physical phenomena can also be complex and in those cases, we as scientists approximate the phenomenon to more easy control for a set of variables, for example assuming a surface to be frictionless or have a certain type of geometry. However, that data do not involve the awareness of one or multiple humans, the foundation for our cognition and the social interaction through which we interact with the world. As Guba & Lincoln (1982, p. 235) put it "we suggest that […] the particular axioms of rationalism are but poorly fulfilled in social/behavioral inquiry". In contrast to this statement, there is, however, a large body of research in PER that deals with social behavior with a quantitative, and perhaps more rationalistic, approach (e.g. Koponen, 2018; Kubsch et al., 2019; Wieman, 2014), that has had influence on both classroom practice (and subsequent studies in PER). A rationalistic paradigm does in that sense have a place in the study of human behavior but just like how research in naturalistic settings (in vivo) may inform subsequent research in artificial settings (in vitro) (Dunbar & Blanchette, 2001) so should quantitative and qualitative research inform each other.

There is a need for an alternative to the rationalistic paradigm when the research concerns data on humans' behavior, thoughts and action, aspects that may depend on thousands of known and unknown variables. This is offered by Guba & Lincoln (1982) through what they call the *naturalistic paradigm* in which some behavior or action, for a specific group of learners, in a naturalistic environment, is more or less plausible, rather than fixed or probabilistic. Their paradigm involves a set of five axioms contrasted with the rationalistic paradigm. The rationalistic and naturalistic paradigms are not opposing, they just have different purposes as in what data they are apt for describing (natural order or social behavior). The axioms of naturalistic inquiry, as formulated by Guba & Lincoln (1982), can be summarized as:

1) The *nature of reality* (involving social behavior) can only be studied holistically and inquiry usually ends with more questions than answers.
2) Researchers *cannot be detached* from their research subjects when it comes to human beings as data. There is always some interaction that influences the result. However, measures can be taken to limit the influence.
3) The aim of the research is to develop some *working hypotheses* that describe individual cases. Phenomena are neither time- nor context-free which makes it difficult or impossible to generalize the findings to situations other than the studied situation. However, the authors add that depending on how similar situations are in terms of contexts and temporal aspects, there may be some transferability from a working hypothesis for a case to another case.
4) There are many factors that shape an action and we as researcher can "at best, establish plausible inferences about the patterns and webs of such shaping in any given case" (Guba & Lincoln, 1982, p. 238). The best way to study these patterns is through *field studies* of the patterns in their *natural contexts*.
5) Research is always influenced by some *values of the researcher*, the *paradigm*, *theories* and *methods* chosen, and *inherent values* in the context studied.

In addition to the axioms, the authors outline six postures which describe common decisions for a researcher of naturalistic inquiry, for example choosing the settings natural to the participants and events studied (e.g. classroom rather than clinical lab). According to Guba & Lincoln (1982), naturalists (researchers of naturalistic inquiry) prefer grounded theory and a design emerging within the natural setting over an a priori theory and designed research sequences. I have, however chosen to include a design in my research outlined in Paper II (although partly informed by the research of Paper I) and have chosen theory a priori as part of the aim of my research is to build on the already established theory of PER. This does not mean that the theory cover the full picture of my findings. For example, the construct of barriers has been informed by previous research but generated as a theoretical construct through the findings of my research and added to the epistemology of the theory chosen a priori.

The axioms of the paradigm that inform my methods, or the assumptions acting as a foundation for my research, thus aim at tolerating the messy or complex real world conditions. What I mean with this is that settings, contexts and phenomena are chosen based on what is natural for the participants rather than the researcher, e.g. the research is carried out with teaching material similar to what they are taught with and in a setting which they are taught in for a specific topic if investigating how students learn that topic. As an example, if one is to study how the intervention of IR cameras affects the learning about heat and temperature, one should carry out the intervention within or in connection with a teaching unit in which the students are learning about phenomena related to heat and temperature. The data collection should be done within the milieu where they are taught, like the lab or classroom, to keep the result as close as possible to the actual teaching and learning that they experience on a regular basis. In addition, any teaching material used, other than the introduced material that is being tested (in this case IR cameras), should be similar to what they use in the teaching unit. The main limitation with research carried out in naturalistic settings is that it is time consuming and difficult to keep some sort of experimental control of the event (it is more messy) (Dunbar & Blanchette, 2001).

An alternative approach, combining real world research with that of research in artificial but more controllable settings, has been offered by Dunbar & Blanchette (2001) who propose that real world research (or in vivo research) is used to generate hypotheses that are then tested in a more controlled, in vitro, environment. My two papers may be viewed as two links in a chain starting from in vivo research and moving towards in vitro in the sense that the study of Paper I emerged through the data which was generated within the naturalistic setting and within the naturalistic instruction (it emerged from the lab instructions of the course that the students' were enrolled in). The setting in Paper II was also naturalistic (one of the classroom in which they had their course lecture in), however, I and my co-authors designed the instructions, or the teaching sequence, partly based on the results from Paper I thus linking the two papers through the shift in in vivo towards in vitro (but still keeping the overall naturalistic nature of the study).

The described paradigm aligns with the results presented in the literature review of how contexts affect learning and reasoning (see *Table 1*) and resembles the naturalistic paradigm as formulated by Guba & Lincoln (1982).

5.2 Prediction-Observation-Explanation

Prediction-Observation-Explanation (POE) is a method, introduced by White & Gunstone (1992) for teaching how to use information for interpretation of experiences or events through the three stages of the method's name. The method is contrasted by the authors with what they refer to as more common way of probing students of their understanding (the single question approach): Given a situation with an outcome, students are to explain the outcome, which is described as a "reproduction of textbook knowledge"(White & Gunstone, 1992, p. 45). This would be like giving the students the observation of the two balls hitting the ground at the same time and then ask them why they appear to do so.

POE involves three stages: Given some information about a topic and initial conditions for some phenomenon, students are to *predict* how the phenomenon will unfold and the outcome of the phenomenon. This is followed by an *observation* and students are asked to *explain* what they have observed, potentially modifying their prediction based on the new information. A typical POE task could be students being asked to predict which ball, of two types, is going to reach the ground first if dropped at the same time from the same height and give a reason for the prediction. They are then to describe what they observe and finally reconcile their initial idea with what they just experienced. In addition to these steps, the authors emphasize the importance of ensuring that all participants know about the initial conditions for the situation, which they are to predict the outcome of.

Similar to how White & Gunstone (1992) contrast POE with the single question approach, POE has been contrasted with *Investigative Science Learning Environment (ISLE)*, a teaching approach described to more closely resemble the practice of science in investigating a phenomenon than what POE does (Etkina, 2015). In ISLE, students are presented with an observational experiment from which they are to infer patterns to the propose explanations that can be tested through experiments either proposed by the instructor or designed by the students. Each experiment should begin with a prediction based on their previously made explanation. The outcomes may disprove some of the predictions and the students can thus reject some of their earlier given explanations. The first steps can be done in cycles to come to a final explanation. Teaching materials such as textbooks should be introduced and read after the experiments.

Etkina (2015, p. 674) describes POE as an approach in which "students are expected to make the prediction based on their intuition or prior experience". This interpretation of POE resembles the ideas of conceptual change in that students are to make their initial and intuitive ideas explicit through the prediction to then encounter a cognitive conflict (Posner et al., 1982) through the observation and accommodate the new knowledge, thus erase their previous naïve ideas. However, this is not how POE has been used in my research. As my studies are framed by the Resources framework, the method is used to *probe* for *productive resources* in the reasoning process about the phenomenon, in which students are to learn what kind of knowledge is useful for what situation rather than, in some way, forget their previous ideas. In addition, POE is exemplified by White & Gunstone (1992) as a method for written tasks. My research involves the analysis of talk and actions and so I have adapted the method for these aspects by adding open questions within the students' predictions, observations and explanations to make the appresent reasoning explicit, e.g. I asked them to elaborate on words that may have been open for interpretation.

Savander-Ranne & Kolari (2003) offer another, more elaborate sequence of probing for knowledge than POE, which they refer to as *Predict – Discuss –Explain –Observe –Discuss – Explain* (*PDEODE*). I have, in a similar way, redefined POE in my studies by building new chains of the parts of P, O and E: The phenomenon in Paper I emerged out of an observation of the students which they were asked to explain and then predict the impact it would have on the experiment. By then providing them with IR cameras, they were given the opportunity to observe the phenomenon again but in a new way through the added thermal image, to then give an explanation. As such, it is no longer a POE in the strict sense of White & Gunstone (1992) but instead a modified method adapted to the context of the research, similar to the modification done by Savander-Ranne & Kolari (2003), rather than just a teaching method.

My studies have been scheduled as closely as possible to the lectures or labs on content relevant to the tasks the students are to carry out, as possible to ensure that the learners have a possibility to not only apply intuition but rather the physics ideas relevant to the task. The closeness in time to the students' regular teaching is also a way of framing the situation in which they participate as similar as possible to "teaching and learning" rather than "participation in research". In particular, previous research have shown that it is necessary to provide students with some sort of pragmatic or simple model on heat flow when supporting learning with technology (e.g. Larsson et al., 2019; M. C. Linn & Songer, 1991; Schönborn et al., 2014). Participants in the studies had access to teaching material involving content knowledge relevant for the tasks, for example a *model relating energy transfer to phase transition* represented on a page, as provided in Paper II and a *lab manual* in Paper I.

The method for which I have probed students' learning could thus be said to be based on POE but with ideas added from both ISLE and PDEODE. The foundation which I have used is illustrated in Figure 5. POE was restructured for Paper I (*O*[17]*PE-OE*). Finally, they were asked for a prediction on how it would affect the result of the type of instructed lab they just had finished. Results from previous research (Haglund, Jeppsson, & Hedberg, 2015; Haglund et al., 2017) suggest that, depending on the level of science they have been taught, students are to varying degrees supported by IR cameras. As the participants in Paper II have less experience in science education than participants in Paper I, a more elaborate version of POE than shown in Figure 5 was used, in which participants were able to discuss each phenomenon in two situations: One everyday situation and one experimental.

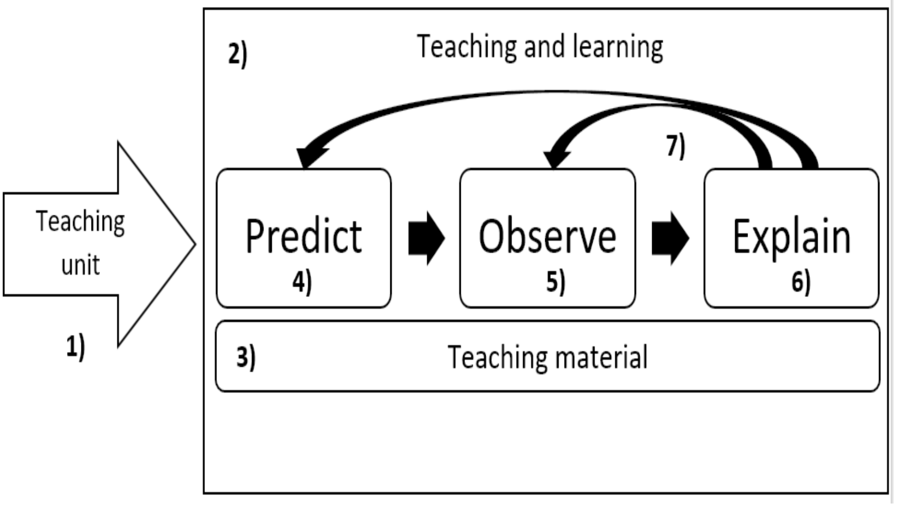

Figure 5. The modified POE approach applied in my research: 1) Physics content: The research is either carried out in or immediately following the regular teaching unit relevant for the phenomena, 2) Framing: The study is potentially framed, by the participants, as part of the teaching unit, 3) Scaffolding: Participants have access to teaching materials potentially supporting their understanding, 4) Given some initial conditions for a phenomenon, they are asked to predict how it is going to unfold, 5) Participants are asked to describe what they observe, 6) The participants are asked to give explanations, which, 7) require them to reconcile their predictions with the observations.

A note on how questions have been posed during the modified sequences of POE: Several of the papers on learning about heat and energy (Erickson, 1979; Kesidou & Duit, 1993; Lewis & Linn, 2003) apply a clinical interview method similar to the method favored by Piaget (e.g. 1971). This method usually involves a loose interview schedule and open-ended questions (Erickson, 1979). My research involves a similar idea on the openness in formulating questions

[17] The observation had already been made when the student notified me about their findings.

to the participants while they are investigating the phenomenon at hand. Questions would be asked to make the students clarify a thought or to push the discussion toward a conclusion. This type of research observations is referred to as *reactive observation* (Angrosino, 2012), an approach in which the participants know the intentions and the role of the researcher and interventions are done by the researcher during the observation, for example by posing open-ended questions.

5.3 Data collection

Three types of participants are included in the data for Paper I and II: primary school teacher students, chemical engineering students and instructors in chemistry (PhD students in physical chemistry).
There are commonalities between the three cohorts of participants in the two papers (illustrated in Figure 6):

1) While the PhD students in physical chemistry (instructors in Paper I) are experienced teachers, the teacher students (students in Paper II) are training to become teachers.

2) While the engineering students (students in Paper I) are training to become chemists, the PhD students (instructors in Paper I) are experienced chemists.

3) Both the teacher students and the engineering students are enrolled in an introductory unit on thermodynamics (physics for the teacher students and chemistry for the engineering students). However, the entry requirements for the engineering program include more experience in science than for the primary school teacher program.

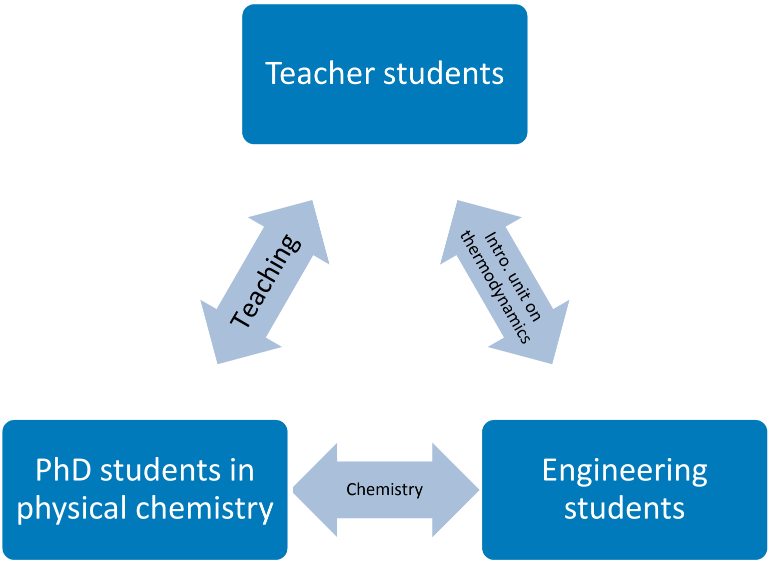

Figure 6. The relationship between each cohort in the two papers, as represented by the arrows.

Research in PER has explored both of these types of student groups in terms of learning, that is students in chemistry (e.g. Dreyfus, Gouvea, et al., 2014; Geller et al., 2013; Greenbowe & Meltzer, 2003) and teacher education (Etkina, Gregorcic, & Vokos, 2017; J. Larsson, 2019; Wittmann et al., 2017) from a PER perspective. My aim in choosing these two groups, however, is not mainly to contribute to these two bodies of research but rather to have a diversity in background and experience of physics when analyzing the affordances of IR cameras in educational settings, and the reasoning processes of the diverse cohorts.

I have described the *temporal orders and contexts*, and the *settings* of the data in Table 6, as these aspects are important in the chosen paradigm. Students in Paper I had access to their lab manual and did initially not have access to IR cameras. These were added as an intervention after the students' observation of the phenomenon and subsequent attempts at formulating hypotheses for the observation. In contrast, in Paper II, students participated in a designed teaching sequence which, for each phenomenon, included an everyday situation, and an experiment for which the students had access to IR cameras. The IR cameras were thus in a way used for intervention in Paper I while they were embedded in the design of the sequence in Paper II. The language used in both data collection was *Swedish*, which was translated to English by me before publication, and after crosschecking the translation with other authors of the papers (see Appendix B). All authors but one (on Paper II) are native Swedish speakers with English as their second language.

Table 6. Overview of the data in Paper I and Paper II from some aspects important in naturalistic inquiry.

	Paper I	*Paper II*
Data	Engineering students in thermodynamics unit	Science teacher students in physics unit on thermodynamics
Thermal phenomenon	Deliquescence/hygroscopy	Phase transitions
Teaching material	Lab manual, intervention with IR cameras	Model relating energy flow and phase transition, IR cameras embedded
Contexts of phenomena	Not having salt in closed container	Accessible and cheap everyday experiments
Setting	Laboratory	Classroom/lecture hall
Temporal order	Within lab session	Following regular class

All sets of data were collected through video recording which was transcribed using *multimodal conversation analysis* as a basis for the transcription procedure (the analysis of Paper II paid less attention to multimodalality than Paper I however). I observed the students in the instructed lab from the start (after they had been informed and agreed on participating in the study). I varied between just observing and taking notes, and video recording and probing the students about their practice. I tried to remain at a certain distance while observing not to interfere too much in their naturalistic practice.

There is something to be said about that balance between being able to probe for students' reasoning and the awareness of being a part of research: The presence of the researcher could potentially lead to the students framing the situation in a different way than they would have if they had not noticed my presence, thus modifying their talk and reasoning in accordance with what they expect is probed for in the research they participate in (sometimes referred to as the *Observer's paradox* (Labov, 1972)). It would have been unethical to not inform the students that they were part of a study and my absence in the room may have resulted in much of their reasoning being appresent and thus unattainable through their talk and actions. I thus had to be there as a reactive observer in addition to informing them (and asking for consent for this) about what they participated in.

5.6 Multimodal conversation analysis

Early research using *Conversation analysis*, studied social interaction through speech, for example by recording conversations, transcribing those conversations and then analyzing structures within those conversations, such as how conversations are ended (Schegloff & Sacks, 1973). It is common for the research applying this method, to aim at recording the data in naturalistic settings, that is in the setting where the type of data gathered is ordinarily produced, thus fieldwork is preferred in collecting the data rather than gathering the participants in a research laboratory where they are prompted to talk (Jewitt et al., 2016). This idea of considering the setting in which the research is carried out is in line with the idea about framing and contextual cues affecting how we learn and reason about a phenomenon or problem. If we keep the setting as close to students' regular teaching settings as possible, the result may also be more close to the result one would have gotten as a teacher or instructor within the students regular learning practice.

As earlier studies have shown (Euler et al., 2019; Fredlund et al., 2012; Goodwin, 1979; Volkwyn et al., 2019), there is a value in adding a layer of analysis of multimodal aspects such as gestures to data analysis of video data. For example, Euler, Rådahl & Gregorcic (2019) found that, in exploring the periods of binary stars through an open-ended digital environment, a pair of students coordinate gestures, speech and body position around a dance which act as a coordinating hub (Volkwyn et al., 2017) for forming explanatory models of the phenomenon.

Later iterations of the method of Conversation analysis do include multimodal aspects of communication as a part of the data that is transcribed and analyzed (data is then collected through video recording). Pioneering research using *Multimodal conversation analysis* include much of the work of Goodwin: Goodwin (1979) included gaze as one of the main modes for analysis when investigating how shifts in gaze aim at distributing parts of the meaning of a sentence so that the part of the sentence deemed to be relevant to a specific person is delivered in sync with the utterance of that part. Another paper (Goodwin, 1994) looks at the professional practice of archeology through how gestures are coordinated with the speech of the practitioners while working with an excavation. Both of the papers mentioned include multimodal conversation analysis as a method for processing and analyzing the data. Multimodal is used in the sense that the paricipants include other ways of communicating than just speech that are deemed to be relevant for the study by the researcher and previous research informing the study.

There are two key principles (Jewitt et al., 2016) for Conversation analysis that have been followed when analyzing the data of Paper I and II:

1) The focus of analysis are video clips. The analysis should stay close to the clip selected. Any claims should primarily be grounded in the data of the chosen clips.
2) Get to know your data. The analysis should be iterative in that the data should be watched several times and at different paces before conclusions are made.

I have watched each data set several times before choosing the clips important for the aim of each study. The choices have then been discussed with the co-authors and the data have been watched in data sessions (researchers meet and watch the clips together). This has been followed by transcriptions of the chosen clips and new data sessions where I and my co-authors have discussed the transcription in relation to watching the clips. Additional iterations followed by new transcriptions and discussions among the authors on potential themes or patterns found in the data. The final transcriptions have been translated for the purpose of publishing in international journals.

In addition to these two principles, Mercer's (1995) *typology of talks* has been used to analyze the patterns of speech of the participants. The original idea of Mercer was to not use the typology as a way of categorizing all observed speech but rather to support an understanding of how talk is used by learners to think together. I have used the *characteristics* (or what Mercer refer to as *speech acts*) of the different types of talk as an instrument to find patterns that holistically fit the type of talk that Mercer describes. For example, talk that largely contain *disagreement* and *individualized decision-making* would be interpreted as *disputational talk*, talk with *repetions* and *confirmations* would be interpreted as *cumulative talk*, etc.

The original transcripts for Paper I included "Body", "Gaze" and "Interaction with artefacts" in addition to "Speech", as seen in Appendix B, but the first three aspects were merged into "Non-verbal actions" and "Speech" was re-labeled "Verbal action" for publishing. Additional information on the posture, and positions of the participants in relation to the IR cameras and the phenomenon (before and after being introduced to the cameras) is provided in Paper I in the form of illustrations, as the paper is centered around the interaction with the IR cameras. Illustrations of the body positions and actions were added together with the transcripts in Paper I (see *Figure 7*).

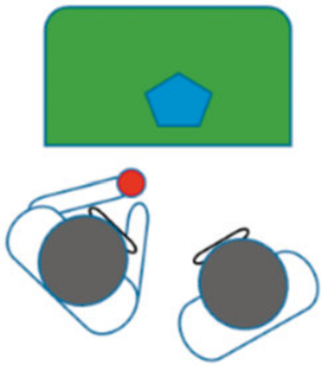

Figure 7. Example of multimodal illustration added to the transcript in Paper I. Red circle indicate a salt in a container that the students had picked up to point out aspects that they had noticed. From Paper I.

Paper II includes less multimodal information than Paper I and the structure of the transcripts is more closely related to traditional conversation analysis in that they mainly convey the speech of the participants (with added clarifications or multimodal aspects whenever deemed necessary to understand the talk). The analysis of multimodal aspects for the paper was done from the raw data (the video), a few of these were added to the transcript for a fuller picture of the situation. For example, laughs added after answers that could show surprise or insecurity, or when one student holds a cup while talking which affect the result of the cup's temperature as the person heats the cup, perhaps without being aware of it.

The final, published transcript only included speech. The difference between the transcription process of the two papers is mainly because of what is being investigated in each study. The first paper concerns the interaction with the IR cameras and the experiments and the laboratory practice of the participants. The second study is more focused on the reasoning processes in terms of what cognitive resources are negotiated and coordinated during the discussions, and how the participants frame the learning.

The transcripts of the papers are available in *Appendix C* and *Appendix D*. An example of the longer transcription process for Paper I can be found in *Appendix B*.

5.7 Trustworthiness

The context in which research is carried out may matter to the results. This is pointed out by Scherr & Hammer (2009) when discussing some results from a paper of Redish et al. (1998). I agree and have tried to keep my studies within the education that the students participate in when I am investigating their learning and understanding.

In relation to proposing a paradigm of naturalistic inquiry, Guba & Lincoln (1982) also suggested four criteria of trustworthiness, equivalent to the criteria of the rationalistic paradigm (Internal and external validity, reliability and objectivity) to answer questions on truth value, applicability, consistency and neutrality. These criteria are as follows:

1) **Credibility**: Given an account of participants' response to the analysis and interpretation of the data generated by the participants, it is possible to determine how believable the output of the researcher's research is. As an alternative safeguard for credibility, Guba & Lincoln (1982) suggest that the researcher gets acquainted with the context, culture and respondents to discern "salient characteristics of both the context and the problem" (Guba & Lincoln, 1982, p. 247). In addition, the researcher should have a prolonged engagement in the environment to ensure that the researcher's presence does not disturb the participants natural practice. This more or less boils down to ensuring that the researcher has knowledge about the participants and the culture that they act in (and that the researcher tries to minimalize the effect of his or her presence on the practice of the participants).

2) **Transferability**: Given that the researcher provides *thick descriptions* (Geertz, 1973) about the contexts of the source and the target, results can be transferred from one situation to another if they are similar "enough".

3) **Dependability:** The emergent nature of designs in the naturalistic paradigm makes it difficult for replication studies. Changes are thus intended in studies applying a naturalistic paradigm. Some dependability, or stability could be achieved if the same researcher carries out a replicative study as the emergent design would be based on the same experience and biases as in the initial study.

4) **Confirmability:** The neutrality or objectivity should be placed on the data rather than the inquirer as the inquirer always will be biased. A way of doing this is to keep records that can be used to trace the data back from published to the raw stage (confirmability audit).

I agree with Guba & Lincoln (1982) to an extent on these criteria but there are aspects where I would give an alternative control mechanism that fulfils the condition for the criteria. For example, the ways that an outsider could control for the quality of research through replications (as in the rationalistic paradigm): A naturalistic paradigm only allows for quality controls if done by the same group of researchers that carried out the initial study and this mean that other researchers have to trust that those researchers would be as rigorous and critical as a researcher who was not a part of the original study. Additionally, using Multimodal conversation analysis as method for analyzing and interpreting some data, each iteration and data session contributes to ensure the criteria of consistency (which the *dependability* criteria is a naturalistic form of).

There are also alternatives to, for example, the *transferability* that elaborate on the nature of generalizability of the type of research that I do. One such alternative is offered by Bassey (2001, p. 6) in his concept of *fuzzy prediction*: "particular events may lead to particular consequences", which is contrasted with scientific generalization: "particular events do lead to particular consequences". Like the initial argument, made by Guba & Lincoln (1982) for naturalistic inquiry as an alternative to the rationalistic paradigm, Bassey (2001) exemplifies the messy nature in classrooms as a reason for finding alternatives in education research to the goal of scientific generalization:

> The teacher may give what appears to be the same lesson in exactly the same way in a second classroom, but the outcome of the second lesson may be quite different because some un-noted variables of the setting, or the class, or individuals within the class, are sufficiently different to affect the outcomes (Bassey, 2001, pp. 6–7).

To then try to replicate a naturalistic study would be similar to replicating the pattern in which a set of feathers fall when throwing them outdoors on a windy day: it is possible but incredibly unlikely that someone would be able to replicate the pattern as just the windy condition is determined by multiple variables. Like Guba & Lincoln (1982), Bassey (2001) argues for a potential of transferability (the "fit" in Bassey's words) between situations that share similarities and that it is necessary for the researcher to provide thick descriptions informing others on the potential of transferability of the results.

The suggestion in the fourth criterion has been followed as the different stages of transcription (and video data) have been kept so that it is possible to find a path back from the published excerpts of the transcript to the raw data (the video data).

An aspect important to the dependability is the inquirer being the same for all data collections thus affecting the participants in the same way through for example what question chosen to pose to the participants.

When Guba & Lincoln (1982, p. 250) propose their paradigm of naturalistic inquiry, they also add that "the naturalistic school is only beginning to develop an arsenal of weapons against the charge of nonrigor or untrustworthiness". Although not considered "weapons", conversation analysis as a method has ways of dealing with the *trustworthiness of analysis* in that the transcription process is iterative with data sessions where researchers meet to check for each step of interpretation of the data. In my case this has been done by me transcribing all video data and then reviewing both the previous step of data processing and the current one, i.e. the video data and the first iteration of transcription, together with my co-authors in a data session. To summarize the measures that have been taken to ensure the four criteria of naturalistic inquiry:

1) **Credibility** – identifying with the participants:
   This can be ensured by, for example prolonged engagement with the site investigated in the study, for example to "overcome distortions introduced by the inquirer's presence" (Guba & Lincoln, 1982, p. 247) and persistent observation to get acquainted with the context. In short, ensure that the presence of the researcher does not disturb the participants natural practice and that the researcher know what aspects that are relevant and irrelevant in the environment. This is achieved by participating as much as possible in the learning context and through my own background as a teacher student (Paper II) and chemistry student (Paper I), two experiences that give me access to the features salient in the environment for an outsider. My participation in the environment of the first study (Paper I) lasted for at least an hour and several hours in the second study (Paper II).

2) **Transferability** – contextual richness in description:
   By describing the participants, the teaching material, the setting, contextualization of problems and the temporal order (see Table 6) I have tried to establish the context that can be compared for similarities when attempting to transfer the results to other situations (to perform a, what Bassey (2001) calls, fuzzy prediction). Additionally, I have tried to find problems or phenomena that are naturally occurring for the participants, e.g. the sequence in Paper I depicts deliquescence which is a phenomenon important to have in mind when experimenting with sodium hydroxide in chemistry labs, all experiments in Paper II relate to everyday situation and are cheap to carry out so that the teacher students are able to apply these experiments in their own classrooms in the future (a goal of the course labs of the course that students were a part of). All teaching material other than the IR cameras is adopted from the participants' regular course work.

3) **Dependability** – iterations of analysis:
   All video data that was recorded, all questions that were posed and the initial transcription were all carried out by the same researcher, and was then scrutinized by the co-authors in an iterative way through

multiple stages of transcriptions in which sequences were chosen, modes were added, removed or combined and speech was translated.

4) **Confirmability** – the history of data processing:
My data is trackable through the stages of processing that it has gone through from the raw data (video recordings) to the published data (transcriptions of clips).

5.8 Ethics

There is a contradiction in carrying out naturalistic research and at the same time considering ethical issues as one of the more important ethical considerations when dealing with human beings is to make them aware of what they participate in, how the data will be handled and for what purposes it will be used (Angrosino, 2012). I have decided to make the information about my research and the participation as clear as possible to the participants by providing them with both verbal and written information in their native language and by protecting their identities as much as possible, for example by avoiding the use of photos of the participants in publications. All participants who wants to participate have also had to sign consent forms with information about the research (*Appendix A*). I have thus followed the two main principles of research ethics (Angrosino, 2012), informed consent and protection of confidentiality in carrying out my research.

Another point of consideration when it comes to research on humans using IR cameras is how to handle the thermal images generated by the cameras. IR cameras generate a dynamic visualization of the environment by exposing aspects relating to temperature. These images may also be recorded as static images and used for research publications or students' project reports. However, aspects that normally go unnoticed and that may be experienced as embarrassing for some students may be highlighted through the camera, for example warm spots on the body, sweating and even information about medical conditions such as rheumatoid arthritis (Pauk, Wasilewska, & Ihnatouski, 2019). I have chosen not to record any thermal images on the participants. The thermal images used have instead exemplified the technology of the cameras and the phenomena studied by the participants.

There are some differences between the paper regarding what formal rules they have followed in considering research ethics, as The General Data Protection Regulation was enforced in 2018:

Data in Paper I was collected before *The General Data Protection Regulation (GDPR)* (European Parliament and Council of the European Union, 2016) became a requirement but the students were informed about the reasons for doing the study, their rights of withdrawal from the study at any moment and that their identities would not be exposed in the publication. Students who wanted to participate signed consent forms (see Appendix A).

Data in Paper II was collected in accordance with GDPR: Students were informed both verbally and through written information about the participation. They were allowed to opt in or out from aspects of the study by checking boxes on the final consent form (see Appendix A).

The data is stored on an external hard drive and shared among the involved co-authors and other researchers that the participants have agreed to include among the people that may have access to the data.

None of the authors of the publications included in this thesis have had any financial support from the company (FLIR) manufacturing the IR cameras used for the studies.

6. Results

This part of the thesis is mainly on the analysis of the data and subsequent discussions of the results. However, as described in part *5. Methodology*, the transcripts for the two papers differ in terms of what aspects of the communication of the participants are included, and in the way POE has been structured. I here include a short description of these differences for each paper under the description of the context for each study.

6.1 Paper I

Paper I is an *in vivo* (Dunbar & Blanchette, 2001) study about the affordances of IR cameras in learning and talking about thermal phenomena grounded in a disciplinary phenomenon, and how talk relates to laboratory practice, more specifically practice that involves technical equipment.

It should be noted that most of the illustrations in this chapter are from the published paper. The Open Access Policy of the journal (Creative Commons) that the paper was published in, Designs for Learning, includes the following statement:

"Authors of articles published remain the copyright holders and grant third parties the right to use, reproduce, and share the article according to the Creative Commons license agreement" (Designs for Learning, 2019).

6.1.1 Context

The data in Paper I involve two engineering students and their instructors participating in a calorimetry lab (part of a unit on thermodynamics) in a chemistry introductory course. The lab involved calculating the enthalpy change of the solution for some salts (of which one was sodium hydroxide) to, among other goals of the lab, learn more about heat and heat capacity.

Initially, a larger cohort of students had agreed on participating in the data collection and I participated as a *reactive observer* (Angrosino, 2012) during their laboratory practice, video-recording the students while asking open-ended questions probing for elaboration and explanations whenever the students were discussing content-related topics such as the decision for insulating the container for the chemical reaction. I looked for talk about phenomena that could be used as starting points for discussions on heat and temperature so that a subsequent intervention with IR cameras could be done to explore the affordances of the cameras.

At one of those occasions, two students notified me that they had observed something that they found peculiar: some of the solid sodium hydroxide, in the form of salt pellets, had been taken out from the container at the preparation bench and then been left out in the open. This initiates the first of three sequences of data analyzed in the paper (the other two being when the students have access to IR cameras and the instructors of the lab observing the same phenomenon with IR cameras). The students had noticed that the pellets had turned glossy and a bit wet. I saw this as a good starting point for formulating hypotheses that could be investigated with an IR camera and thus asked them what the reasons for their observation was. The students were later (sequence 2) introduced to IR cameras to observe and explain the same phenomenon again.

Sequence 3 involves the instructors: Two PhD students in physical chemistry, acting as instructors in the lab, were asked to perform the same task as the students , to compare the students' use of the cameras, and their talk while investigating the phenomenon, with instructors who have much more experience with the lab than the students. These two PhD students came from two different research fields of physical chemistry (material and inorganic). This type of in vivo examination of a type of, for the context of this lab, "expert" talk may also be considered a contribution to the need for research on in vivo language of "experts" working with a task related to thermodynamics, as called for by Brookes & Etkina (2015).

The three sequences had a POE structure altered from the one presented in 5.2 Prediction-Observation-Explanation: The students followed something closer to OEP-OE (Observe, Explain & Predict – Observe & Explain) as the students began with an observation (Sequence 1, line 1-2), were asked for potential explanations (Sequence 1, line 3-14) and to predict how it would affect the experiment (Sequence 1, line 15-20). They gave an explanation (Sequence 2, line 6-7) again after observations with the IR cameras (sequence 2, line 1-5). The instructors only participated in the intervention with IR cameras and were there probed with OE, that is Observe (line 1-6) and Explain (line 7-15).

Note for the reader: All lines referred to in this chapter can be found in Paper II.

6.1.2 The data

This paper thus concerns two types of participants: students (engineering students) and instructors (4^{th} year PhD students in chemistry) in a calorimetry lab which was part of a larger unit on thermodynamics. Goals of the lab included learning more about heat and to plan and carry out the experiment: dissolving salts in water to determine whether they are *exothermic* or *endothermic* and to calculate the *enthalpy change* of the solutions by applying the *Born-Haber* *cycle*. All students that agreed on participating through informed consent, and that signed the consent forms, were recorded while working with their instructed lab. However, I was surprised that two of the students actually wanted me to attend to a phenomenon that they had noticed while working with their lab instructions, and that they seemed genuinely interested in sharing this discovery with me. The sequence began when I posed a question that I usually started my probing with when walking up to some students: "How is it going?".

The pair of students had made the observation during their setup for measuring the temperature change of dissolving sodium hydroxide in water (using a coffee cup calorimeter). When I asked them to elaborate on their finding and give some potential explanations, they formulated four hypotheses before continuing with their instructed lab. When finished with their instructed lab work, the students were invited to carry out the same experiment in a qualitative way, with IR cameras. The phenomenon, deliquescence, that the pair of students earlier had discovered was also added as a part of the inquiry with IR cameras.

The instructors were introduced to the same set of phenomena that the students had worked with when the last students had finished their instructed lab work. In this way, the data consisted of two pairs of people that could be referred to "novices" and "experts" in relation to each other (the instructors have more experience of the disciplinary content than the engineering students).

When structuring the transcripts of all students and organizing them by themes (step 2 and 3 in *Appendix B*) I found that this subset of data could be used to answer *RQ1* (on affordances of semiotic resources of IR cameras).

The part on deliquescence is the target for Paper I and the original transcripts of the data are available in *Appendix C* .

6.1.3 Transcription

An example of the full transcription process (the seven major steps of iteration) can be found in *Appendix B*.

The raw data is in the form of video, approximately 154 minutes for the larger data set, and some written notes. The chosen sequence, and the interventions with IR cameras that followed is about 40 minutes in total. When only including the investigation of deliquescence with IR cameras in the video data of the intervention, the sequence with the students and instructors is each about 2 minutes. Mutlimodally transcribed, this amounts to 9 columns of types of information and 20-30 rows of lines of communication (Step 5).

I watched each video-file and wrote a text on my initial observations (Step 1) before initiating the transcription just to get an overview of the 154 minutes of data that I started out with. The first iteration of transcription was basically a text with the names of each person talking and some comments in brackets what each person points or refers to when using words as "there" or "here"

(Step 2). Step 3 involved finding some patterns or themes across all transcripts that were relevant for the research question on the affordances of IR cameras (for example engagement with the semiotic resources of the tool or phenomena involving temperature change and transfer of heat) and sections of the data (the pair of students and the instructors investigating the phenomenon of deliquescence) were chosen for the study.

The first multimodal categories were added in step 4 (in addition to speech). These were at the time referred to as "motor skill activity" (embodied action) and "sensory activity" (vision), both of which was re-labeled into three new categories in step 5: Body, interaction with artefacts (experiment, equipment and cameras) and gaze. The transcript was then adapted for publication and illustrations of the participants were drawn in step 6. A final edit was done to the transcript to fit the format of the journal (step 7).

6.1.4 Analysis and discussion

The analysis compares the pre-intervention (no IR cameras) with the intervention (access to IR cameras) of the students instructed work, and the both interventions of the students and the instructors in regards to how the interact with the phenomenon and tools, and how they talk in their discussions on the phenomenon and the tool.

Overview of the three sequences

The first sequence, or subset of data, was initiated when the two students notified me about an observation that they had made during their instructed work: The salt that they were going to pour into a calorimeter with water had started to "melt" and "get sticky" while left on the lab bench. The student pointed at the features they found relevant (Figure 9) while describing their finding. They ended the sequence by moving back to the experiment (Figure 8).

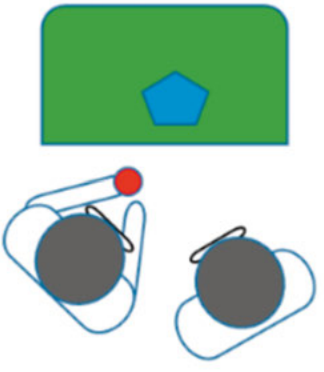

Figure 9. Illustration of the students during initation of sequence 1. Lab googles indicate the direction of the gaze. The red circle signifies the container with the salt. From Paper I.

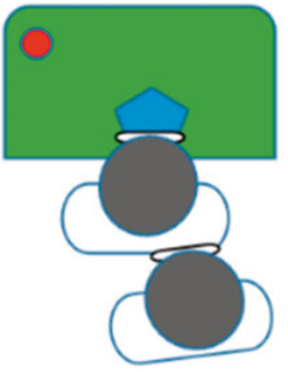

Figure 8. Positions of the students when continuing with their instructed lab (line 13) and the experiment of dissolving the salt in watet within a calorimeter (the blue pentagon). From Paper I.

Sequence 2 follows the same pair of students, as they observe the same phenomen but with access to IR cameras. The students are reminded of the initial observation that their attention was drawn to (the salt being wet) and are asked to describe their observation made with the IR cameras

The final and third sequence involve the instructors using the IR cameras for the same phenomenon as the students. The instructors were informed about the situation and immediately gave a full description of the phenomenon to the engage in exploratory talk while testing different explanations.

The analysis is summarized in *Table 7* and *Table 8*.

Table 7. Patterns of talk, interaction, body and gaze in the three sequences analysed in Paper I.

Sequence	*Participants*	*Type of talk*	*Types of interaction with IR cameras and experiment*	*Body position*	*Gaze*
1	Students	Exploratory	IR cameras were not available	Shifts: towards and away from bench	Shifts: each other, salt and bench
2	Students	Cumulative	Fixed: IR cameras Colors mapped to explanation	Fixed	Fixed: display of IR cameras
3	Instructors	Cumulative → Exploratory	Shifts: IR cameras moved towards and away from salt. Salt moved on the table to shift what is displayed.	Shifts: towards and away from bench and salt.	Shifts: each other, display of IR cameras and salt

Talk, actions and framing

A number of points may seem surprising at first, for example that the students became less dynamic in terms of body movement and that they shifted from exploratory to cumulative talk when getting access to the IR cameras. Previous research (e.g. Haglund, Jeppsson, Hedberg, et al., 2015; Haglund, Jeppsson, & Schönborn, 2016) has shown that IR cameras invite to *instant inquiry* in which students can come up with questions on the spot and test them with the cameras. This is described as a type of *epistemological framing* by Haglund et al. (2015) that, as they show, may not depend on the cameras but rather on the individual learners; some wants to stick with the instructions and some wants to explore more freely. The fact that the students did not take the opportunity to engage more with instant inquiry could thus be a result of the individual students epistemological framing of the situation (follow the instruction).

Returning to sequence 2 and 3 of Paper I in which the participants had access to the IR cameras: While the students were keen on following the task of explaining the phenomenon that they had encountered before, the instructors manipulated the experiment more freely to test their ideas, which suggests a framing of the situation more similar to the instant inquiry-type of framing. In addition, the instructors engaged in cumulative talk while collecting a body of data with the IR camera to form the subsequent the discussion from, and shifted to exploratory talk, a negotiation or synthesis of their individual reasoning, when explaining the phenomenon. In contrast to the students, the instructors continued engaging in instant inquiry while explaining the phenomenon. The framing does, however, also involve a conceptual component (what is the situation about in terms of content?) which is further discussed below.

The difference between sequence 2 (students) and 3 (instructors) can be elaborated on even further (as summarized in Table 7): The students' initial, exploratory type of talk, is in line with the result of Andersson & Enghag (2017) in that it is accompanied by the creation of some new, shared, knowledge and the synthesis of ideas through the hypotheses generated by the students. They do, however, not have a way to test their ideas and so they break the *ecological huddle* (Figure 8) by returning to their instructed laboratory work.

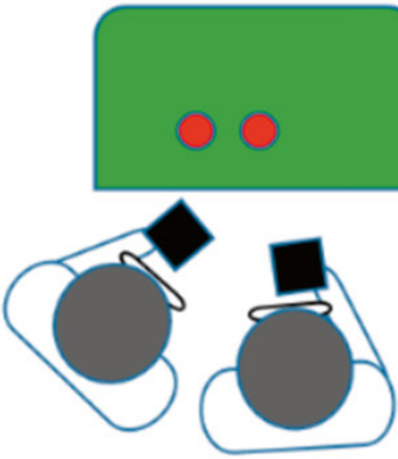

Figure 10. The positions maintained by the students in the second sequence. The black squares indicate the IR cameras. Each student looked at the display of the camera that they were holding. From Paper I.

Ecological huddle and talk

When getting access to the IR cameras they form an ecological huddle around the phenomenon directed through the IR cameras (Figure 10) and shift to cumulative talk as they get access to the IR cameras while observing the phenomenon once again. This is also in line with the result of Andersson & Enghag (2017) as the cumulative talk in their data is used when having access to equipment that allow them to confirm one of their hypotheses: That the salt has absorbed water from the air and reacted with it , thus completing the task.

During this sequence, ending the students' investigation of the phenomenon, the students cumulate the information that they can discern in the situation.

The instructors, on the other hand, begin their sequence by forming an ecological huddle similar to the students (Figure 11a) and b)). However, they alter this formation by moving away the IR cameras from the line of sight between themselves and the experiment, thus observing aspects of the phenomenon with their naked eyes (Figure 11c)). In doing this during the initial cumulation, they are able to link the information available to them from both previous knowledge about aspects visual with the naked eye (like the wetness of the salt) and aspects provided by the IR cameras, to get an initial idea about what they observe, e.g. that the salt is hygroscopic and that the reaction is exothermic.

Cumulative talk is in both cases used to make *explicit readouts*, sharing the information among the participants and linking previous knowledge of each participant to observations to form a synthesis of knowledge. Kluge (2019) showed that this is a useful strategy on the way towards productive reasoning when working with a simulation on heat transfer. In this case, the IR camera acts as that simulation when the participants make their readouts. An IR camera is, however, not a simulation per se but, like the simulation, it acts as a *filter* for the impressions from the environment that the participants act in. As such, the students' fixed gaze on the IR cameras indicate that they attend to the aspects associated with temperature and heat, enhanced through the camera as a range of colors and a dynamic value or number that changes depending on where the hair-cross is pointed at.

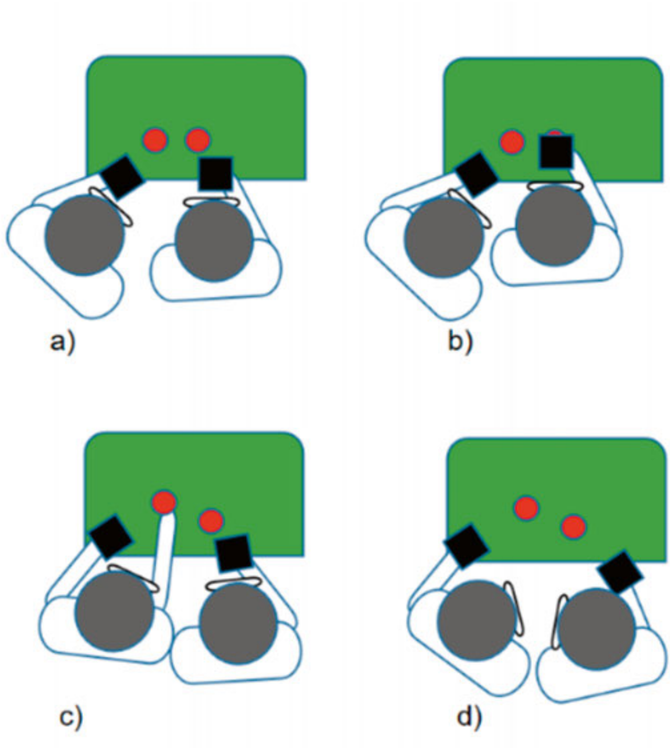

Figure 11. Black squares indicate the IR cameras, red circles the containers with salt and lab goggles indicate the direction of their gaze. ***a)*** *initial position.* ***b) & c)*** *shifts during the cumulative talk* ***d)*** *the gazes of the instructors shifted between the directions of a) and b) and the gazes in d) during the more intense discussions. From Paper I.*

Reasoning

As mentioned, the instructors shift into exploratory talk after they have shared the information available to them and they are asked to explain the reaction. The first explanation is the least detailed of the ones given and through each challenge it gets more and more refined. The question is what drives the instructors in challenging and testing each others explanations. We know from earlier research that "experts"[18] tend to give multiple levels of responses when predicting or explaining a phenomena in science. The instructors are both experienced with the phenomenon as they have instructed the lab several times and although deliquescence is not explicitly brought up in the instructions, it is still critical to have the hygroscopic property of the salt in mind when instructing students in a lab like this. The first explanation given by one of the

[18] Defined as researchers and teachers in the disciplines (chemistry and physics) at university level, in the study of Lewis & Linn (2003).

instructors, “Sodium hydroxide dissolves in water”, could be considered correct although a bit rough. However, as the instructors are in a sense experts on this phenomenon, they probably realize the basic nature of this explanation which compels them to look for a more fine-grained one which is “correct” in a more disciplinary sense.

As an analogy, if one would ask a first-year student in physics a question which requires a short reasoning process to give a somewhat correct response, like “Why would an ice cube melt when taken out from the freezer?” would the student give a more elaborate explanation than “Because the room is warmer than the freezer.”? In case that the answer to this is yes, could it thus be that depending on the minimum effort in reasoning required to give a productive response to a question determines the “fine-grainedness” or detail of the response? If the instructors experienced the task of explaining the reaction observed in sequence 3 as “too basic” it could have compelled them to challenge each other until they had a more refined explanation that would be considered good enough for members of their discipline. This explanation for the “catalyst” of the exploratory talk of the instructors could be explored more in future studies (for example by giving students with less experience than the instructors a, for them, basic phenomenon to explain).

Semiotic resources and affordances

The researchers manipulated the experiment and varied the ways they investigated it, especially when gathering and sharing information through explicit readouts during the section of cumulative talk. By doing this, they varied the semiotic resources involved (the *color* image and *numbers* change when moving the camera which is done through the *form* of the camera).

The colors, numbers and the form of the IR camera are types of of semiotic resources, each contributing to the affordances of the IR cameras. An overview of the affordances of a collection of semiotic resources can be found in *Table 8*.

Table 8. Overview of the affordances of the set of semiotic resources of a specific semiotic system involved in the IR camera. The functions are either explicit in the data of the participants (they refer to them in the talk), or implicit (the participants attend to them through gaze or in other non-verbal ways).

Semiotic system (of the cameras)[19]	*Function*	*Participants*	*Main affordances*
Colors[19]	Initiate and frame the reasoning	Students (explicit) Instructors (implicit)	Attention to thermal phenomenon
Numbers[19]	Support the interpretation of colors	Students (implicit) Instructors (implicit)	Measurement and quantification
Form[19]	Allow for the shifts in interaction with IR cameras and experiment	Instructors (explicit)	Spatial mobility

So each semiotic resource (e.g. red, white, the handle form and the value of room temperature) are lumped together with similar resources that belong to the same semiotic system in the first column of *Table 8*. The students fix their attention on the colors, or really the thermal phenomenon that the colors map, e.g. exothermic reaction. This forms a *shared point of attention* for the students, much in the same way as the cameras enable a shared point of attention by previous studies (e.g. Jeppsson et al., 2017). The colors are then translated[20] into "warm", which is then explained to be casued by the exothermic reaction that has started as the salt attracts water from the surroundings.

[19] Semiotic system is used in

Table 8 but I do not claim that the system itself has the affordances. It is rather the set of semiotic resources of that semiotic system available to the participants in the context they are in, that has these affordances (e.g. the semiotic resources of red and blue of the semiotic system of colors). I have chosen to use semiotic system in the table for the sake of communication, as a more proper heading would have been something along the lines of "the set of semiotic resources made available through the IR camera in the context of a learning unit for the specific type of cohort that is using the tool". Each set of semiotic resources has been labeled with the semiotic system instead of naming each possible semiotic resource that may have had the affordance ascribed to the set of semiotic resource (e.g. the range of temperatures displayed could vary between 20-70 ^{0}C depending on the investigated phenomenon).

[20] I have chosen to not use the term transduction in this case as the meaning transferred from the colors is not transferred to other semiotic systems (other than how it is communicated). The meaning goes from color to a memory of a feeling (warm) to a disciplinary concept (exothermic reaction). When memory has been proposed as a semiotic system or mode (R. Samuelsson, Haglund, & Elmgren, 2016), it has been challenged by the community of researcher involved

Although they do not explicitly refer to the temperature on the screen, the temperature supports a translation of sorts of the colors: What is blue or red in the thermal image varies with the maximum and minimum temperatures within the thermal image so the interpretation of the color need to take the values of the temperature into account when describing it as "warm" or "cold" (e.g. a surface with the maximum temperature of -2 ^{0}C would be white/red for temperatures around -2 ^{0}C.).

As a contrast, the instructors did not refer to the colors or the numbers but they did, at multiple occasions, refer to visibility of the phenomenon, as in "You see", "You clearly see" or "You can see". Additionally, in Line 2-4 (see Paper I), they moved the container with the salt to observe the transfer of heat to the bench (which would have been visible without the IR cameras). The interpretation, that moving the container support their initial observation of an exothermic reaction caused by the attraction of water, could have been made through the colors, the numbers (temperature) or both. Regardless of which semiotic resource was involved, it would require at least one of the semiotic resources for the phenomenon to be visible to the instructors.

The affordance of the colors, attention and interpretation are related to the conceptual framing: A focus on some aspects or cues is attained by the colors, contextualizing the phenomenon through similarity with familiar events and the resources activated through association (e.g. red is associated to situations concerning danger, warmth, fire, love, etc.) thus forming the participants' conceptual framing[21] when they interpret the situation through this lens (this is a phenomenon about warmth, heat transfer or high temperature). The colors affords attention to the thermal phenomenon (they conceptually frames the situation) and subsequent, more detailed investigation is done through the numbers that afford measurement or a quantification of the phenomenon. To change the ways the participants (in this paper, the instructors) observe and interact with the phenomenon, they change the distance or angle between the cameras and the experiment. This spatial mobility is the affordance of the form of the IR cameras.

The affordance of the form relies on the other two semiotic resources (when moving the IR camera, the colors and the numbers change) and vice versa. In this way, the collection of semiotic resources "[…] becomes a meeting point of theory, existing knowledge and experience […]"(Kluge, 2019, p. 1091) and in providing visual cues for associations to heat and temperature, the IR camera filter out irrelevant aspects and keep those relevant to the task and so forming a basis for attention. This feature of the IR cameras has in previous research (Jeppsson et al., 2017) been referred to as a *thermal loupe*

in research on multimodality and Social Semiotics. This has lead me to instead use "translate" for the transfer of meaning in this sequence.

[21] Remember that framing "[…] is to interpret it [the situation] in terms of structures of expectations based on similar events."(Hammer et al., 2004, p. 9).

and other research on educational technology has discussed this in terms of *filter* (Volkwyn et al., 2019), *reducement of visual distractors* (McElhaney et al., 2015) and *constrainment* or *enforcement of an interpretation* (Scaife & Roger, 1996).

It seems that one, or a combination of more than one, of the semiotic resources involved in the IR cameras affordance are used both by learners to learn more about a phenomenon but also by instructors, a type of disciplinary experts, to deepen their understanding of the disciplinary content, thus providing "[…] access to disciplinary knowledge." (Fredlund et al., 2012, p. 658). As such, the IR cameras is a type of tool that have both pedagogical and disciplinary affordance without having to "unpack" the semiotic resources to shift disciplinary affordances to pedagogical affordances which has been suggested as a way to shift between types of affordances of a semiotic resource (e.g. Airey & Eriksson, 2019).

6.2 Paper II

Compared to Paper I, Paper II is a move towards an in vitro type of study (the context or setting is that of their regular teaching (e.g. naturalistic) but the sequence is designed) which aims at investigating how contexts of tasks and students' resources affect their reasoning about thermal phenomena grounded in everyday situations. The central phenomena in this study were evaporation and condensation (e.g. the teaching target was to relate energy transfer, evaporation and condensation).

6.2.1 Context

The data in Paper II involve a group of five teacher students who just had participated in a lecture in a physics teaching unit on heat which is a part of the full semester course on science that all primary school teacher students, that are to teach science, take.

The students were introduced to a teaching sequence on *phase transitions* and *energy transfer*, with the goal or *teaching target* of relating the phase transitions involved with each other and heat or energy transfer. The sequence initially involved four phenomena[22], and an *IR camera* was available as supporting tool. Each phenomenon was embedded in a part (here A-C, but originally A-D) that included an everyday situation and an experiment using an IR camera for observation.

[22] The sequence initially included fusion, or melting as a last part (D). This was, however, excluded as the phenomenon, melting of ice by adding sodium chloride, was conceptually too complex for the students. In addition, the first three steps (A-D) captured transitions between gas and liquid but the fourth part would add a transition outside of this.

The data collection included an additional group of teacher students participating in the same teaching sequence at the same occasion. Both groups were video-recorded during the sequence. The final data used in the publication included five teacher students reasoning through three phenomena of which each had an everyday situation and experiment associated to it. An outline of the three parts can be found in Table 9. The three parts of the teaching sequence in Paper II.

Table 9. The three parts of the teaching sequence in Paper II.

Part	*Phenomenon*	*Everyday situation*	*Experiment*
A	Condensation	Boiling water on rocks in a sauna	Boiling water in kettle
B	Evaporation	Stepping out from a shower	Water sprinkled on hand
C	Equilibrium of evaporation and condensation	Cup on table	Cup on table Paper on cup Shift paper on cup

The sequence starts out with an overview of the sequence: The estimated time, amount of phenomena and experiments, information on POE as a method, information on IR cameras, promotion of writing and drawing pictures of thoughts and arguments and a reminder that they will not be graded or assessed on the tasks. A brief description on the teaching material is presented (Figure 12) to the students.

The teaching sequence that then follows is available (translated into English) in Paper II (p. 579):

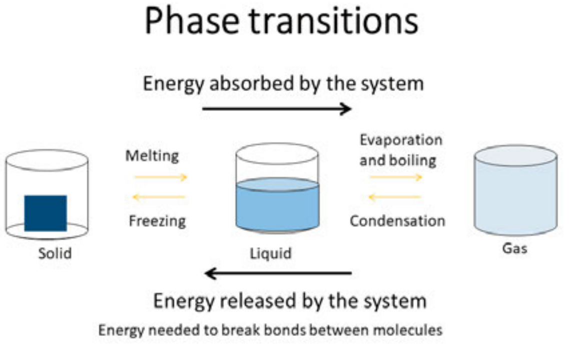

Figure 12. Teaching material available to the students in the study of Paper II as illustrated in Paper II, p. 578. Translated into English for publication.

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 your 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."

The presentation of each part (A-C) included an image of the situation: Three guys sitting in a sauna with the text "It's like a sauna in here.", the First World

Problems meme with the text “I was taking a shower and left the shampoo bottle on the sink – so I had to step out of the warm shower and into the cold bathroom to get it” and an image of a paper and a glass of water.

Through the parts of Table 9, and the method POE, the sequence structure can then be formulated as:

Everyday situation → POE experiment → Everyday situation → POE experiment → Everyday situation →OE-POE experiment

Each part is initated by relating to some common everyday situation which is associated by a feeling of “warm” or “cold”. This is then shifted to the experiments related to the sensations. Step C. include multiple parts of POE for the different shifts in the experiment (when moving around the paper to shift the equilibrium).

6.2.2 Phase transitions

The phenomena summarized in Table 9 will briefly be described before turning to the content of Paper II as to give an indication of what would be considered productive in the students' reasoning processes. The descriptions are mainly conceptual and qualitative as the context in which the study is carried out follows the syllabus of the course that the students are enrolled in, which has a conceptual focus on the science content. The situations that include the phase transitions in this sequence are also designed to be in line with the syllabus which aims at providing the students with opportunities in which they can apply their knowledge about everyday phenomena of science. In addition, they are to practice laboratory activity and discuss observation in a scientific way. Each everyday phenomenon is thus followed by an experiment relating to the everyday situation.

The first situation that the students encountered in the teaching sequence was the feeling you get when sitting in a sauna and water is thrown on the stones that can have temperatures of 500-800 ^{0}C. As a result, the water is almost immediately transitioned into steam which, through convection reaches the individuals sitting in the sauna. From a vapour pressure curve, Hermans & Vesala (2008) show that 80 mbar, or 8% of humidity, lead to saturation at around 40 ^{0}C. As the average humidity of saunas is about 8% (Vesala, 1996), increasing the humidity by throwing more water on the rocks lead to condensation of water onto the skin of individuals sitting in the sauna, assuming that human skin warmed in a sauna, is close to 43 ^{0}C (Vesala, 1996). The condensation leads to release of latent heat (energy transferred through heat transfer from the phase transition) which gives a sensation of “warmth”.

An analogous experiment to this was included in the teaching sequence: The boiling of water in a kettle and the feeling of “warmth” when holding a hand above the kettle. The transfer of heat to the hand when holding it above the kettle can be visualized through the temperature change detected by an IR camera. Now, this experiment is not equivalent to the situation involving the sauna as the humidity and temperature in the room is much lower than in the sauna. As such, it is likely (depending on how far away the hand is from the kettle) that the steam condensates in the air before it reaches the hand. Much of what is experienced as a transfer of heat due to phase transition is thus really transfer of heat from liquid water. The experiment will, however, be treated as if the hand was held above the boiling surface of water.

Another aspect that is not be covered in the teaching sequence is the work done by the steam on the surrounding air. The aim of this sequence is to support an understanding heat transfer in relation to phase transition, not energy transfer due to work.

The second situation is that of experiencing "cold" when stepping out from the shower due to the shift from a humid environment with running water against the skin (behind the shower curtains) to a dryer one where the water begins to evaporate thus requiring energy through heat transfer which is experienced as "cold". The analogous experiment for the situation involves sprinkling some water of room temperature on the arm to observe the effect of evaporative cooling with an IR camera while simultaneously feeling the "cold" (thus mapping "cold" to evaporative cooling).

The third situation involves something that often may go unnoticed for short periods of time: When leaving a cup of water on a table over a longer period of time, the result of the evaporation will get more visible as more water is removed from the cup. The water surface keeps a slightly lower temperature than the surroundings as a result of the evaporation requiring energy[23]. Condensation is also present as a phenomenon but it is, relative to the amount of water that transitions into gas, a much smaller amount of water that transitions from gas back to liquid. By adding a sheet of paper on top of the cup, thus "trapping" the water, breaks the equilibrium between evaporation and condensation as the water no longer is exchanged between the cup and the surroundings, but rather between the cup and the sheet of paper. When the water condenses on the paper, the temperature is increased due to heat transfer from the phase transition. The heat is transferred through the sheet and visible to an IR camera, but only for a while as the process eventually will reach a thermal equilibrium with the surroundings. Removing the paper will lead to evaporation dominating on the paper, which requires energy and as a result, the temperature of the paper instead decreases.

[23] The size of the effect depend on the ratio between the surface area of the water and its volume, and the humidity of the room.

6.2.3 Transcription

The data generated by the teacher students for Paper II was collected through video recording to then be transcribed. The students sat around a table while one of the students recorded their discussions and practice. I probed the students for clarifications during their discussions. The collected data was shared between the authors who knew Swedish (and thus would understand what the students were saying) before a first iteration of transcription was done. I made a first analysis of the initial transcript which was then sent to the co-authors for comments. All the comments were then discussed at a meeting involving all the authors. Some aspects found in the analysis, for example that the laws of thermodynamics were brought up by the students after getting access to the IR cameras and the experiment, were chosen to be included, as examples of some patterns, in the publication.

6.2.4 Analysis and discussion

The full analysis can be found in Paper II. I will here touch upon some of the major points that contribute to the final synthesis of the two papers. The explanations given by the students for the first task (the sauna and the boiling water in a kettle) shifted from the everyday situation to the experiment in the ways the students framed their explanations: The first explanations were centered on the *human body* while much of the reasoning about the experiment was centered on the *second law of thermodynamics* (this was then used as a main resource in explaining the other experiments as well) and *heat rises* (sometimes combined with the second law of thermodynamics).

Reasoning

The students' reasoning in relation to the paper on the cup, (outlined in *Figure 13)*, initially focused on the empty cup and they thus reasoned that 1. Water would drip down which leads up to the reasoning that 2. energy would move down into the empty cup. However, when 3. the shower and sauna, and the sensation of cold, from part A and B are added to the reasoning, they move on from focusing on the empty cup and reason that it has to be a matter of 4. evaporation which 5. requires energy. There was a risk, in 3. that the reasoning would have gone elsewhere (the dotted arrow) as air or wind blowing was mentioned in relation to the sauna and the shower as cause for the sensation of cold. This could have been a barrier but it was avoided through the subsequent productive resources (evaporation & requires energy). However, *wind* and *air* were brought up several times during the teaching sequence and did at times, like in part B, lead the reasoning off-track. The close association between air and heat was already shown by Erickson (1979) and Wittman et al. (2019) has later shown how it can act as a distracting barrier in problem solving.

When observing the temperature decrease of the evaporative cooling in the cup with water, the students begin discussing the temperature of the paper and whether the water will wet the paper:

> Teacher student 4: *"That we experience it to get colder when we have moist on our skin. I wonder if the paper will become moist if it has a lower temperature."*
> Teacher student 2: *"But the paper is not 37 degrees"*
> Teacher student 3: *"What degrees do the paper have then? 28 point. Higher than the water anyway."*

They are here testing if the second law is applicable in explaining the outcome of putting a piece of paper on top of the cup with water, e.g. that the paper will get colder. And when actually getting to explain the outcome, after having observed the increase in temperature on the paper, they respond with:

> Teacher student 1: *"It rises. The heat rises."*
> Teacher student 5: *"Yes, the heat rises!"*
> Teacher student 2: *"So all the heat in the cup. It is insulated. It is like insulation!"*
> Teacher student 2: *"So it insulates the heat, so that everything settles in the surfaces."*

Here they add heat rises which acts as a barrier and leads them to add the explanation of insulation, i.e. if heat rises how does it "stop" and increase the temperature of the paper? If the paper is "cold" and it insulates the cup, then it transfers or settles in the paper.

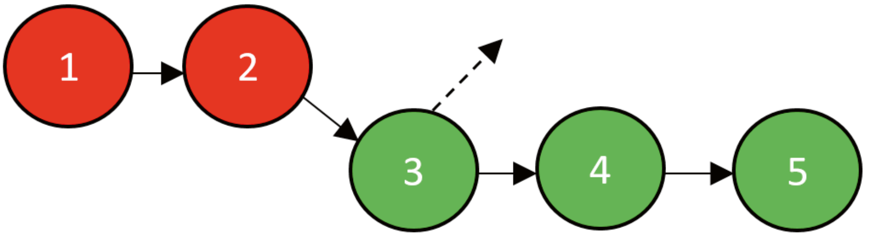

Figure 13. Students explaining what happens with the condensed water on the paper when moving the paper from the cup with water, in part C of Paper II, to an empty cup. The arguments were quite linear in this case but a more complex reasoning may have included multiple reasoning units (e.g. the circles) connecting to one or multiple other units. 1. Water drips down, 2. Energy moves down into the empty cup, 3. The sensation of cold from walking out from the shower or sauna (may be caused by some wind or air blowing, represented by dotted arrow), 4. Evaporation and 5. Evaporation requires energy.

Let us assume that heat rises implies the convection and that the students then have in mind that there is evaporation of water from the cup with water (they give this explanation in the situation of a cup of water standing on a table). The reasoning can then be illustrated as in *Figure 14*: heat rises and the second law of thermodynamics potentially leads to the students missing the condensation in the reasoning. That heat "settles" or is transferred to the paper is caused by insulation in the students' line of reasoning and thus not connected to the phase transition that should have informed the heat transfer in the reasoning.

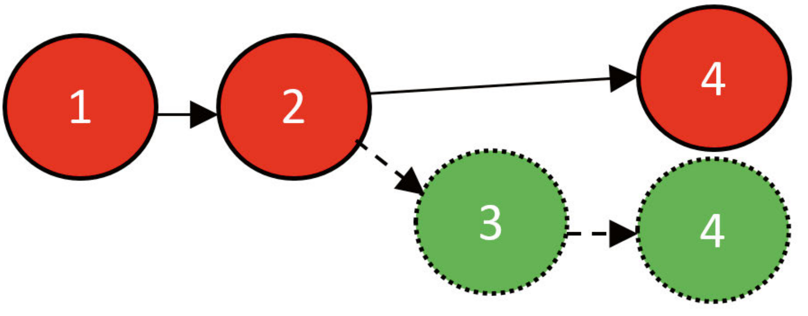

Figure 14. The reasoning about the increase of temperature of the paper being put on top of a cup of water. Dotted lines and circles are potential lines and units of reasoning. 1. Heat rises and 2. the paper insulates the cup so 4. the heat settles in the paper. If 3. condensation would have been brought to the reasoning then 4. would have been used informed by 3., e.g. heat is transferred (latent heat) to the paper as the water condensate.

Talk, action and semiotic resources

The talk of the students had the characteristics of exploratory talk but contained characteristics of cumulative talk at the initial observations with IR cameras during the experiments, when sharing the information that was gathered by the participants looking at the IR camera. The information shared during the cumulation of shared knowledge was that of either readings of the IR camera (colors and temperature) or sensations (it feels warm, wet or cold). The observable features visible with the naked eye were not explicitly shared when having access to the IR cameras, for example the water "disappearing" when evaporating from the hand in B or the apparent dry paper that contained condensed water in C.

Both colors and numbers were explicitly mentioned during observations with the IR cameras. The observations were, however, in contrast to observations made by the students in Paper I, initiated by reference to sensations in A and B. The observation of the experiment in C, though, when a paper is put on top of the cup, started with the surprised remark of one of the students "It became red!". This was then translated into "Yes, the paper became warm!". In this case, the outcome of putting the paper on top of the cup has not been experienced in the same sense as the other two experiments (through the sense of touch) and may therefore be more surprising to the students than the observations of part A and B. This may have caused the more immediate reaction of referring to the semiotic resource of red to initiate the reasoning process which is then translate into warmth through association of resources (red to warmth). In this sense, the psychological principle on successful visualization of energy, as formulated by Goodhew et al. (2015, p. 1063), that "[…] having the opportunity to see something which is usually invisible attracts attention"[24] could be restated as "having the opportunity to see something which is usually not *sensible* attracts attention", with the attention to the thermal phenomenon afforded by the semiotic resources of the IR camera in this case.

Framing, context and coherence

At times during their investigation of the phenomena with the IR cameras, the students tested their own ideas through instant inquiry, much like how the instructors in Paper I move the container with the salt. For example, by checking the temperature of their toes to compare with the temperature of the fingers or by testing the experiment in B with multiple participants to compare the sensations. This is, like the actions and practice of the instructors, an indication of the students' epistemological framing of the situation: they do not interpret the purpose of the situation regarding their behavior to be just about following the instructions to the letter but experience a certain degree of freedom in their investigation of the phenomenon.

As shown in the literature review (e.g. Chi et al., 1981; Driver & Warrington, 1985; Wittmann et al., 2019), it seems that it is important to consider the contexts chosen for problems or tasks on energy analysis or thermodynamics. Students tend to attend to visual or literal cues and features when reasoning about potential solutions to the problems. The everyday situations chosen in each part of the sequence were chosen with this in mind. It seems that it paid off in terms of the students' framing of the sequence as they managed to anticipate each subsequent situation in the previous part (A-C) and referred to the previous parts in the final part (C) thus indicating that the students framed the sequence as a coherent whole:

[24] This was formulated as one of four psychological principles that underlie successful visualization by Goodhew et al. (2015) but the idea behind this specific principle comes from Gardner & Stern (1996).

- **A → B:** To explain the sensation of cold felt after having held a hand above the kettle with boiling water, one student said "[…] it feels cold. The feeling you get when you step out from the shower into the room and … get cold."

- **B → C:** To convince a student who was hesitant in explaining the sensation of cold occurring as a result of evaporation, one student argued "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."

- **C → A & B:** "But we know that if you step out of the shower then you have water on your body, or when you step out of the sauna, then you have this moisture. […] Then you feel…then you get cooled down." This is then followed, through exploratory talk and explicit readouts, by the reasoning evaporation → requires energy → it gets colder.

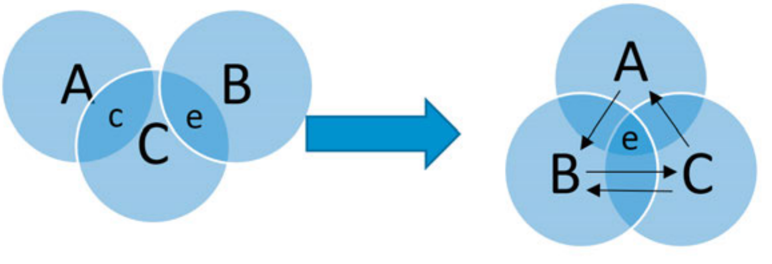

Figure 15. The designed structure aimed at linking part A to C through condensation (c) and B to C through evaporation (e). The students instead found coherence between all of the parts through evaporation by expanding the situation of A to include the step of stepping out of the sauna. The arrows point from the current part to the following part according to what resource the students anticipated from the upcoming situation (e.g. shower situation from B used in A is illustrated as arrow from A to B).

As a result of the students anticipating the situations of each part, "Stepping out from a shower", "glass of water on a table" and "stepping out from a sauna" were all used as resources in productively arguing for or explaining observations resulting from evaporation. It should be noted that "Stepping out from the sauna" was used as a resource to expand the situation in part A to include evaporation as a phenomenon, even though it was designed with condensation in mind, see Figure 15. In addition, each anticipation in A and B was made during the use of IR cameras in the experimental stage, but linked the phenomenon to the situation in the next stage (rather than the experiment).

Resources and barriers

It thus seems that the design with these situations matched the set of resources one could expect teacher students with this experience to employ in reasoning abut evaporation. As an implication of this finding, it may be wise to not just consider the context of one problem or task but also how the context varies from problem to problem in relation to the content it aims to teach.

Although this sequence seems to lead to productive reasoning around evaporation as content, it did not lead to productive reasoning about condensation to the same extent. A potential explanation for this can be found in the literature review on resources: Some resources, considered productive in some contexts, may hinder the access to resources productive for other contexts, for example the ideal gas law (D. T. Brookes & Etkina, 2015; Leinonen et al., 2009; Loverude et al., 2002) as a barrier in understanding heat as a process or employing the first law of thermodynamics. I call these kinds of resources barriers, a term borrowed from Loverude, Kautz & Heron (2002, p. 146): "Their confidence in this law [ideal gas law] seemed to be a significant barrier to consideration of the first law of thermodynamics".

One of the main resources employed throughout the sequence by the teacher students is the second law of thermodynamics which they remembered from their previous teaching in the course that they participated in. The formulation of the law taught in the course was "Heat is always transferred spontaneously from a warmer to a colder body". The teacher students either explicitly referred to the second law of thermodynamics, talked about it in terms of how " […] energy wants to be distributed equally […]" or described how heat goes from warm to cold. The second law of thermodynamics led the students to talk about heat in terms of air, steam or vapor moving, in other words convection, and was at times used together with reasoning about how heat rises. It was thus productive in reasoning about types of heat transfer but resulted in them straying away from discussions on phase transitions (it is especially apparent in the discussion about the shower in part B).

In addition, the students applied a kinetic model, like when reasoning about how water molecules in the steam slowed down when they got in contact with the hand in part A. This model acted as a barrier in reasoning about condensation when trying to predict what happens when putting a paper on top of a cup of water in part C.

In contrast, resources related to the body like the sensation of warm or cold, types of prototypes of previous experience of these sensations, were productive in initiating the reasoning process about each phenomenon as it seemed to encourage the students in giving suggestions on explanations for the phenomena based on the familiarity of the sensations. It is, however, difficult to determine whether the productivity exclusively relied on the familiarity with the sensations, the contexts or a combination of both (it is unlikely that someone has had the experience of being in a sauna without the experience of feeling warm).

Additionally, it should be noted that body-related resources also acted as barriers after at occasions after the initiated reasoning process, for example when explaining why it gets warmer in a sauna after having poured water on the rocks one student responded that the water on our skin acts as insulation "[…] which keeps its own heat […]". It thus seems that cueing for embodied experience is useful as a start in teaching about heat but could lead to barriers in the reasoning process if the learners overrely on this resource.

7. Synthesis of results and discussion

To look for additional patterns across the two papers and form a synthesis of the two, an additional analysis has been carried out on the data sets for Paper I and Paper II (see *Appendix E*). As the comparison requires information about the actions of the participants and the transcript for Paper II is less multimodal than the transcripts for Paper II I have had to view the video data again together with the transcripts for Paper II to analyze how the teacher students used the IR cameras, their gestures and what type of information they discussed in general (e.g. information gained through the IR camera, the naked eye or sensation).

Before moving on to the synthesis of the two papers in the light of the research questions, I would like to summarize some of the points made in the analysis and discussion of each paper:

Paper I:

- The students shifted from exploratory to cumulative talk when shifting from explicit readouts and generation of hypotheses, to the access of IR cameras and a more instructed context in which confirmation of a hypothesis was the outcome.
- The instructors shifted from cumulative to exploratory talk when shifting from explicit readouts and observation, to explanations of the phenomenon.
- The ecological huddle was centered around the phenomenon being discussed for both students and instructors. The students "broke" the ecological huddle when they returned to the instructed lab, as they could not confirm any of the hypotheses. The instructors altered the ecological huddle by moving their cameras in order to gather information with their naked eyes to combine with the information that was provided by the thermal images. This led to the basic response ("Sodium hydroxide dissolves in water") that initiated the exploratory talk which was fueled partly by the information gathered during the cumulative talk and partly by the "basicness" of the question relative to the instructors' experience of the phenomenon (see hypothesis on this mentioned in the chapter on Paper I).
- The semiotic resources of the IR camera, the colors, the numbers and the form mainly afforded attention to thermal phenomenon, measurement and spatial mobility respectively.

- The students' observation with the IR camera was initiated by the students explicitly referring to the color of "red", which was then translated to "warm"; an indication of the conceptual framing of the phenomenon to be about heat and related resources.
- The IR camera seem to have both pedagogical and disciplinary affordance as it supported the explanation for the students and compelled the instructors to give a more detailed and elaborated explanation than the explanation of the students.
- While the students gave a short concise explanation, the instructors gave a more elaborate and detailed explanation of the phenomenon even though they could have reasonably stopped at the first given explanation. This may potentially be related to the experienced "basicness" of the task: If the instructor experienced explaining deliquence as too easy they would push each other forward through exploratory talk to refine the explanation into one which is more detailed than the initial one. In contrast, the students experienced their explanation as "good enough".
- The experience and role of the instructors and students in the course that they participated in, affected the epistemological framing of the situation which may have resulted in the cumulative talk of the students when observing and explaining with the IR camera, and the exploratory talk of the instructors for the same tasks. The restrictive and instruction-focused framing of the engineering students may have led to the quick explanation when using the IR cameras (as they had already formulated hypotheses in a structured way in sequence 1).

Paper II:

- The students anticipated each situation in the experiment of the previous part for A and B to B and C, and referred back to the situations of A and B to initiate a productive reasoning process, involving both exploratory talk and explicit readouts. This ended in an explanation of the experiment in C with evaporation.
- Students were engaged in cumulative talk during observations but shifted to exploratory during explanations of the phenomena (while using the IR cameras in a dynamic way). This could be an indication of an epistemological framing of the students that is close to instant inquiry. The result of the framing is a looser structure in the investion process which may have resulted in the students taking a longer time in finding a productive path of reasoning for the phenomenon (compared to the engineering students).
- The students explicitly attended to sensations and thermal information when using the IR camera.

- Similar to the instructors of Paper I, the students engaged in instant inquiry (to less extent than the instructors) and interacted more with the experiment than the students in Paper I when they used the IR cameras.
- The second law of thermodynamics and "heat rises" acted as a barriers for reasoning about condensation but a productive reasource for heat transfer and evaporation in the concluding part of the teaching sequence.
- The laws of thermodynamics as technical terms were brought up with the use of IR cameras and experimentation.
- The semiotic resources were not as emphasized in the talk of the participants of Paper II as in Paper I. The students referred to colors and numbers during observations but did not initiate A or B with explicit references to these. The observation of the experiment in part C, however, was initiated by explicitly referring to "red" which was translated to "warm". An indication of the conceptual framing of the phenomena to be about heat and related resources.
- Body-related resources were productive in the initation process of the discussion.

7.1 Talk and affordances of semiotic resources

The instructors share knowledge through *cumulative talk* when initially encountering the experiment to then negotiate and elaborate through *exploratory talk*, starting out from a quite short explanation and then through something similar to Socratic questioning leading to a more sophisticated explanation.

The engineering students use *exploratory talk* during their explanation and prediction of the phenomenon in sequence 1[25] but shift to *cumulative talk* when getting access to the IR cameras for additional observation and explanation of the phenomenon. This may be a result of the students encountering unfamiliar content and technology at the same time (the instructors may not have had experience of the technology but they had experience of the physics content of the phenomenon). However, it seems that the students coordinate the *semiotic resources* of the tools in a *productive* way to explain and confirm one of their earlier stated hypothesis so in the end, even though they maintain cumulative talk during their use of the cameras, they manage to find a satisfactory and productive reasoning. This may be thanks to their *structured* formulation of hypotheses done in sequence 1: The reasoning process became

[25] The observation of the students was made before I got to the students but they summarized the observations in line 2 of Paper II and tied it to an explanation. It is therefore difficult to say if the observation that they had made earlier on was done through cumulative or exploratory talk. The exploratory talk was however used in the attempts at explaining the phenomenon and predicting the impact of the phenomenon on the calorimetric experiment.

straight forward as they already had a set of hypotheses to choose from and could thus just confirm one of them.

The teacher students shift between *exploratory talk* and *cumulative talk* depending on whether they use the IR cameras and what type of activity they are engaged in. They engage in cumulative talk when observing phenomena with IR cameras and engage in exploratory talk when predicting or explaining the observations (with or without the cameras).

All participants seem to engage in *cumulative talk* when investigating the phenomena with IR cameras. The instructors shift to *exploratory talk* when asked to explain the phenomenon. However, they continue using the IR cameras during their exploratory talk to argue for a certain explanation or to challenge the other's explanation. The teacher students did occasionally also use the IR cameras during their explanations as seen in *Appendix E* .

The fact that much of the students' talk when using the IR cameras was that of interpreting information and agreeing with each other's statements is a contrast to previous research on IR cameras that has emphasized the explorative role of the cameras through the *instant inquiry* it invites to (e.g. Haglund, Jeppsson, & Schönborn, 2016). However, as shown in the analysis of Paper II, the teacher students seem to explore ideas on the go (instant inquiry) when having access to the IR cameras (like measuring the temperature of their toes). It is just that the information added by doing this does not lead to any elaborations or productive explanations and they do not really contribute to the reasoning process leading up to a final explanation.

Andersson & Enghag (2017) show how students engage in *cumulative talk* when collecting data and *exploratory talk* when analyzing the results. The former is also true in my research as all the participants' observations with the IR cameras are made while engaged in cumulative talk. However, the engineering students explain the encountered phenomenon in sequence 2 of Paper I while still engaged in cumulative talk. Like mentioned before, this may be a result of them having formulated hypotheses during sequence 1 in a way that they could agree on just confirming one of those without having to challenge the reasoning again (the negotiation was made in sequence 1 already). The instructors and, to a lesser extent, the teacher students, did use the IR cameras to collect additional data while explaining phenomena through exploratory talk, for example when instructor 1 challenged the explanation of instructor 2 by collecting additional data in line 13 in Paper I.

The IR camera focuses the learners' attention on the *critical aspects* of thermal phenomena and allows for a certain extent of *disciplinary discernment* (Eriksson, Linder, Airey, & Redfors, 2014) as they at times recognize salient aspects of the phenomena. The learners also show signs of recognizing the *affordance of spatial mobility* ("It [the temperature] decreases and increases because of us moving" in observing the paper on the cup in part C of Paper II) or how small changes in temperature that go unnoticed by their senses may be shown by the camera (In predicting what happens to the temperature of the paper in part C of Paper II: "Will we notice any difference now?” “Maybe if we use the IR camera”). Making aspects that usually can not be discovered, like the small temperature change of the paper, visible is what attracts our attention according to Goodhew et al. (2015). Thus, for our limited senses, it is the unusual change is what focuses our attention according to this view. However, the semiotic resources making the aspect available in this case are common to our everyday life as we see the colors all around us. It is just that these specific colors draw our attention in a specific way: The colors of grey and black may not have had the affordance of attention to thermal aspects as they are not associated to resources linked to thermal phenomena. An area in a thermal image where red is replaced with black could, for example, have been interpreted as “soot” or “grime” rather than “warmth” or “heat”.

The engineering students are less engaged with the IR cameras (they vary and manipulate to a lesser extent than the instructors and teacher students). The affordance of the form as a semiotic resource is thus only expressed in the static stance maintained throughout the second sequence in Paper II: The form supports attention but not variation as it becomes part of the students’ ecological huddle but is not used to break the huddle at any point (like it is for the instructors). A possible cause for this restricted use is the *epistemological framing* of the situation as instructive. The teaching sequence is also instructive but the teacher students use the IR camera more freely by for example moving the camera to observe the experiments at different angles. This may, perhaps, have to do with the epistemological framing affected by the environment and course in which they participate in: While the teacher students participate in the teaching sequence within a classroom and a course that is supposed to support them in relating the science to everyday ideas and practical experiments, the engineering students act in a chemistry lab and chemistry course designed to train professional experimentalists. As the instructors are already trained in these basic skills in being meticulous in the lab, they may feel more free to improvise and test new ideas than the engineering students. It thus seems that experience also affects the epistemological framing but perhaps in another way than what one would expect: More experience leads to an inquiry type of epistemological framing. Additionaly, other larger aspects may influence the framing, such as the already mentioned effect of the course or environment, or the way that tasks throughout a teaching sequence are contextualized (are they grounded in everyday situations or the discipline?).

Another possible explanation for the, compared to the instructors, more restrictive actions of the engineering students could be that the engineering students experience the experiment as less familiar than what the instructors do, or than what the teacher students do with their teaching sequence which anchors (Clement et al., 1989) the phenomena in everyday situations. However, this is again about the *larger aspects* affecting the *epistemological framing* (how are the tasks contextualized and how experienced are the participants in the discipline).

It should be added though that the teacher students did get to spend more time with the IR camera and thus get more used to the technology which could have contributed to their more explorative use of the camera compared to the engineering students. In the end, the engineering students manage to *confirm* one of their hypothesis. The teacher students also use the cameras for *confirmation*.

The instructors do not explicitly refer to the *semiotic resources* of the cameras as they are acquainted with the theory of the phenomenon but they often keep their gaze on the display of the cameras and talk about the phenomenon "through" the camera (they talk about the appresent (Marton & Booth, 1997) aspects). As such, it seems that they begin by having an idea about what the phenomenon is about and then test this idea with the IR cameras to get *confirmations* through *measurements*. For the disciplines of physics and engineering, IR cameras are often used to check technical equipment used in experimentation, evaluating some properties of materials or to confirm/reject a hypothesis about some phenomenon. The cameras could thus be proposed to have *disciplinary affordance* for "experts" as the instructors use the cameras in a productive way to deepen their disciplinary explanations, in verifying the quality of the experiment and for confirmation of hypotheses (like when one instructor moves the container of the salt to check for heat transfer to the table).

Both engineering and teacher students directly refer to the colors and temperature when they make their observations and explanations, and all observations, no matter if they are made by students or instructors, begin[26], with attention on the information generated by the IR cameras. Colors seem to frame the situation for the students while the temperature readings are used for more detailed (although often qualitative) measurement. However, the semiotic resources are not directly referred to by the instructors (they look at the screen and move it close to the experiment when initiating their cumulative talk). This may be an additional sign of the disciplinary affordance of the tool as the disciplinary aspects of the phenomenon that the colors represent are appresent and yet the instructors directly refer to these aspects through the semiotic resources provided by the camera: e.g. red and a high value of T (semiotic resources) indicate an exothermic reaction (appresent). From a cognitivistic perspective, the semiotic resources can be thought of as *visual cues* providing support in *filtering* the information available in the environment. In a meta-analysis on *dynamic visualizations* in science education (McElhaney et al., 2015) it is shown that simultaneous conceptual representations in dynamic visualizations has a negative effect on learning but found two exceptions (Lee, 2007; Lee, Plass, & Homer, 2006) where *iconic representations* supported *conceptual representations* of heat and pressure. The duality of the

[26] The beginning of the observations have been analyzed as two steps, for example one student saying something and the other responding or one instructor giving two statements (see Appendix E)

numbers and the colors of the IR cameras could be similar to this exception as the numbers (symbolic) represent the temperature for the point which the cross hair points at in addition to the maximum and minimum values of the image. Interpreting the temperatures is constrained by the colors (the iconic representation) that indicate a range of temperatures spanning across the thermal image. This effect is however limited to novices[27] as the iconic representation is extraneous for experts[28]. However, in the data, it is possible to see that the instructors do attend to the iconic representation (the colors), it is just not explicitly referred to by the instructors (see the analysis of Paper I where both number and color is marked as implicit). By moving a container they actively generate a red mark on the table from the heat transfer which they use in their cumulative talk.

The *form* of the IR cameras allows for variation as the thermal image shifts when moving the camera. This variation may lead to additional steps of elaboration and reasoning as appresent aspects may become present when observing a thermal phenomena at a new angle (just like how the legs of a table at close distance become present when squatting or moving away from the table).

Another affordance of the IR cameras that is present in both the instructors' and the teacher students' reasoning is how the tool *"pulls them back"* in, or refocuses discussions on heat transfer when the reasoning begins to wander away from the productive path (because of a *distracting barrier*). A similar result is shown by Kluge (2019) when students use a simulation that acts as a *focal point of talk* which encourages talk about the relevant aspects of the phenomenon the simulation illustrates. However, Kluge (2019) also shows that the simulation encourages explorative discussions which was not the case in my studies when the students used the IR cameras. Simulations can, in contrast to the observations done with the IR camera, be run several times and users of simulations are aware of this. Some phenomena do "run" for longer time than other so that it is possible to change angle of observation or manipulate the experiment while it is running. This requires knowledge about the "life" of the phenomena though, for example knowledge that the exothermic reaction will be going on for some time as the salt is absorbing water from the surrounding air. The instructors are probably aware of this and can thus use a more dynamic approach in investigating the phenomenon than the engineering students.

The teacher students did engage in explorative discussions after having used the IR cameras though, which indicates that the focus afforded by the IR cameras lasts longer than the use of IR cameras, possibly an effect of the students framing the situation in a way when using the IR cameras which they then keep when initating explanations.

[27] Low prior knowledge learners in the paper.
[28] High prior knowledge learners in the paper.

7.2 Barriers and productive resources

The probably most prominent *productive resource* that students in both Paper I and Paper II referred to was the *sensations of warm or cold* which, in the longer reasoning process of Paper II, usually triggered some other resource such as when concluding that it feels cold having had water condensing on the hand in A and given some time for evaporation, which led to association to stepping out from the shower (and thus the situation of B). Many resources were productive in that they were used to dodge a *barrier* and return the reasoning back on the main path, for example when predicting that the water in part C would evaporate and cause the paper to crumble (argued from the case of cooking lentils) is challenged by adding that the rate of water vaporizing is too slow (perhaps distinguishing steam from water vapor) to make the paper crumble. Additional resources strengthen this argument, for example that it takes some time for water to evaporate from a glass of water standing on the bedside table. Archived papers being destroyed because of moisture is then brought up as another potential barrier but this is resolved with another productive resource: By adding that the paper on the cup would have one side exposed to the surrounding air and one to the water in the glass and that there is some kind of competition between the water inside the glass and the air outside of the glass.

Barriers include *resources* that lead the students to *"wander"* in their reasoning in a way that the reasoning strays away from the main content (e.g. evaporation, deliquescence, condensation) or the path of productive reasoning. This process is in cognitive science called spreading activation (Collins & Loftus, 1975), a concept that has been incorporated into the Resources framework (E. Redish, 2004). Several minor barriers were found in the analysis, both of the common sense and disciplinary type. These include, but are not limited to, the bathroom door in part B of Paper II, the empty cup in part C of Paper II and sweating in part A. The students centered their reasoning around the empty cup that is used to hold the paper when moved away from the cup with water in C. The cup did not have any purpose other than holding the paper when it was moved away from the first cup with water. The students were distracted in their reasoning as the cup acted as a barrier similar to how students were distracted by "air" being included in a problem on energy conservation (Wittmann et al., 2019). In this case, however, the students managed to move away from the barrier by adding the, for the situation, productive resources of the sauna and the shower. Other minor barriers include the residual water in sequence 1 of Paper I which the students use to formulate one of their hypotheses. They manage to continue with their reasoning and formulate additional hypothesis as the cleanniness of the preparation bench ("But I thought it was supposed to be dry over there") act as a productive resource to lead them back to a productive path of reasoning and the formulation of additional hypotheses. Another minor barrier was that of the door in reasoning about why it felt cold when walking out from the shower: Much of the discussion revolved around whether the door would be open or closed (even though the task was to reason about stepping out from the shower curtains).

Two major barriers can be found in the teacher students' reasoning: *The second law of thermodynamics*, that together with *"heat rises"* leads the students to conclude that there is no phase transition when the water vapor in the cup (part C) reaches the paper (however, there is an adsorption that forms the basis for condensation). In addition, a *kinetic explanatory model* also acts as a barrier at times (in the students' reasoning, molecules move fast in a gas, then slow down and after that condensate).

There can also be something said about *the relationship* between *resources*, as interpreted within the Resources framework, and the *semiotic resources* of the IR camera. The best possible example of this can be found when the students directly refer to a semiotic resource, for example both the engineering students and the teacher students begin their investigations with the IR cameras by referring to *red* and then *warm* which leads to a *productive reasoning* and finally sound explanations. For the teacher students, however, this is done on the third experiment (part C) which involves a more unfamiliar outcome than the other two experiments, one which does not directly involve previous embodied experience. They may not have "seen" the temperature change of their skin when water is condensing (part A) or evaporating (part B), but it is clear from their discussions that they have had the sensations of water evaporating from, or condensing onto their bodies. It is thus the novelty in the phenomenon of the experiment in part C that seems to add to the surprise that makes them explicitly emphasize the semiotic resource that immediately draws their attention: the shift from something invisible to something visible that Goodhew et al. (2015) proposed as the first psychological factor underlying successful visualization but with the more specific formulation in that it is the shift from something previously unnoticed to something noticed that draws the attention. The experiments in part A and B had been noticed at some earlier occasions but then as embodied experiences, the experiment in C with the paper added to the cup, could not have been noticed in that way and was thus a previously unnoticed phenomenon. The phenomenon of deliquescence is in a similar sense an unusal, and perhaps unnoticed, phenomenon for the engineering students (something that they may have experienced without being aware of it) which add to their surprised reaction and emphasis on the color of red (and subsequently white) in sequence 2. In the same line of reasoning, the instructors did not explicitly refer to the colors as the phenomenon is common to the environment which they practice in and should thus have been noticed at earlier occasions when for example looking for sources of errors for experiments in their research.

The subsequent reasoning in coming to a somewhat satisfactory explanation for the observation takes different lengths of time for the two student groups in Paper I and II. That is, the time spent on elaborating and challenging potential explanations after the association of red to warm is much longer for the teacher students than the engineering students. The teacher students encounter *barriers* such as "insulation" before arriving at the explanation of condensation of water onto the paper. This explanation is made in the attempt at explaining the observations made when moving the paper from the cup rather than at the time when they are asked to explain the observation of putting the paper on top of the cup in the first place. The short path of reasoning of the engineering students may be ascribed to the *structured* attempt at explaining the phenomenon in sequence 1: the engineering students had already then formulated a set of hypotheses and could thus with the help of the IR camera confirm and reapeat one of the hypothesis. The perhaps more *unstructured flow of reasoning* of the teacher students may thus be ascribed to the fact that they participated in a teaching sequence where they were presented with phenomena and situations rather than discovering them on their own in a more loose and unguided inquiry.

The concept of *framing* is here the key to connecting the concepts of resource and semiotic resource: The *semiotic resource of red* supports the *conceptual framing* of the situation as a situation that is about heat and warmth (as red is associated to warmth or energy (Kress & van Leeuwen, 2002)). The resources being coherently activated when handling the IR cameras, i.e. the framing, are associated to the semiotic resources of colors employed in the thermal image, this could include resources such as "energy", "warmth" and "flames" or "cold" and "calm" (to give some common associations to red and blue (Kress & van Leeuwen, 2002)). So, a semiotic resource carries some meaning or association that lead to the activation of a coherent set of resources which frames the situation.

In short: *barriers* can be identified as *distractors* in reasoning processes. Sometimes they recur, and distract, multiple times in a reasoning process and act as a *major barrier*. At other times they just distract the attention at one occasion and act as a *minor barrier*. Barriers seem to be more problematic in an *unstructured* flow of reasoning process (the *epistemological framing* for the teacher students) than when the reasoning is *structured* by formulating hypotheses as defined potential explanations like the engineering students did. What is considered a barrier at one part of the reasoning process may however become a *productive resource* at another part if it does not distract the reasoning (an empty cup could have as well been planned to provide some meaning to the experiment). Productive resources "correct" the reasoning by returning the process to the main path again (often challenges or counter-arguments to the barriers). The *semiotic resources* of the systems of colors, numbers and form that are involved in the IR camera *afford* attention to thermal aspects, measurement and spatial mobility.

How explicit the reference to the color red of the camera is seems to relate to the novelty of the phenomenon, especially in regards to the lack of embodied experience of the experimental activity. Making something that is usually invisible visible (J. Goodhew et al., 2015), or rather something that is has not been sensed visible, seems to lead to the explicit reference of red.

7.3 Coherent framing across contexts

Two aspects were built in to bridge all the contexts in the design of the teaching sequence of Paper II already: Asking and encouraging the use of the students' *sensations* in and *experience* of the everyday situations and the *semiotic resources* of the IR camera.

Many of the papers in the literature review on thermodynamics and education touch upon observable features, visual cues or literal features as something that is problematic when students attend to them as a primary source for information. For example, the discrepancy between novices and students when they are to categorize problems on energy conservation (Chi et al., 1981) and the students' reliance on *literal features* may lead them to approach problems in different ways even though the problems really are the same from an expert point of view.

Numbers and colors as *semiotic resources* of the IR camera can be said to form the basis for some observable features and invite to a certain type of framing in which discussions revolve around the concept of heat. In contrast to much of the previous research (e.g. Chi et al., 1981; Clough & Driver, 1985; Driver & Warrington, 1985) that shows the problems with *observable features*, or really the associations made to these, the dynamic visualizations that the colors and numbers provide in my research seem to be productive resources in talking about heat. For example, by association to warm or hot, red and white contribute to a *pedagogical affordance* of the IR camera.

Observable features, literal features and contextual cues all relate to the context in which a problem or task is situated. By adding the thermal layer of the IR camera to a situation, the framing shifts into one where certain aspects are filtered out and others are emphasized. This is a result of both the first and second function of a physics device proposed by Volkwyn et al. (2019) in that the camera *intensifies* the information in the environment to make it visible, and in that the camera *filters* out much of the irrelevant information as everything observed with the camera is interpreted through a thermal lens. The intensification does not completely fit with the description of Volkwyn et al. (2019) as it translates a signal of infrared radiation (through the assumed emissivity and Planck's law) and then generates the image which is more like a representation than an intensified signal. However, this is not a necessary condition for the talk about heat as is also shown in the data of Paper II, where the students talk about heat and energy transfer before even observing the phenomena with IR cameras. This instead has to do with the already established context of each situation that initiates each part of the teaching sequence (A-C). By asking for how the different situations feel, the students are led into discussions on warmth and coldness which at times is pushed into discussions on heat transfer and thermodynamics as the contexts invite to this. Additionaly, in Paper I the students talk about heat in the formulation of their hypotheses, much thanks to the aspects that they had paid attention to at the beginning: the liquid water that had formed near the salt (which was also interpreted as the salt melting). They could recognize that water mixed with sodium hydroxide would transfer heat which they added when asked how the phenomenon would affect the result of the experiment that they were working on. Both information gathered with the *naked eye* and *embodied experiences* of hot and cold thus seem to play a role in supporting reasoning around heat and energy transfer. Yet, it is difficult to deny the important role that the semiotic resources of the IR camera contributed with in the reasoning about heat transfer (and phase transition). The reasoning of the teacher students did at times focus on irrelevant aspects (barriers) and wandered away from the task at hand through spreading activation (Collins & Loftus, 1975) but when using the IR camera to check for changes in the thermal phenomena they were pulled back in the main path of the reasoning, *stabilizing* the reasoning. It did however also lead them to the wrong conclusions when they got confusing readings from the camera (like reflections on tables of infrared light from lamps or their bodies).

The students in Paper II did not seem to have any trouble in moving between the situations of the three parts and recognized them as similar and coherent (as seen in the students' anticipations in each step) so this was not a *barrier* in the sense that Chi et al. (1981) seem to describe it. The "*closeness"* of the contexts in the three parts that lead to the students framing the sequence as a coherent unit. This is similar to the *bridging analogies* proposed by Clement, Brown & Zietsman (1989) and further developed by Clement (1993). One could ask why an instructor should not just explicitly ask how the situations or analogies relate to each other. Clement (1993) describes this as a strategy that will fail as interviews where this strategy has been used show that students tend to dismiss the relevant aspects that relate the situations to each other. Bridging analogies instead offer an alternative where an intermediate analogy that links the situations is presented to the students, a so called bridging analogy. Clement's (1993) examples include the analogy between a hand pushing down a spring (anchoring the knowledge in intuition) and a book on a table (the target that are to be explained). The bridging analogy in this case would be a book on a flexible board or springy mattress. There are indeed similarities to the teaching sequence in my research in which each everyday situation could be interpreted as the anchor and the phenomenon in the experiment as the target. However, my teaching sequence included several *anchors* and targets that holistically were *framed* by the students as *coherent* (the first two experiments lead to the subsequent situations as productive resources).

When relating the contexts to each other, the students expanded part A to include the phenomenon of evaporation (walking out from the sauna feels cold and it feels cold after having had steam condensing on the hand). This strategy of manipulating the contexts to "fill in" holes in a potential coherence could be interpreted as the students generating their own analogies by building on the already provided situation of the sauna.

7.4 Research questions

Returning to the research questions posed in 3.5.1: With the analysis in this synthesis in mind, in addition to the contexts of the involved studies, the background of the applied theoretical frameworks and literature review, it is now possible to give some potential answers to the research questions of this thesis.

7.4.1 RQ1: Affordances of semiotic resources of IR camera related to resources and framing

RQ1: What are the affordances of the semiotic resources of the IR cameras, in undergraduate students' and instructors' investigation of thermal phenomena, in investigating thermal phenomena in a teaching unit on thermodynamics, and how do the semiotic resources relate to the participants' framing and resources employed in their investigations?

There are three semiotic systems involved in the meaning-making of the IR camera: colors, numbers and form. Semiotic resources of these systems that are used by the participants include red, white and blue, temperatures between the maximum and minimum values for the phenomena investigated (e.g. boiling water or sodium hydroxide reacting with water and evaporating water from cup of glass with room temperate water).

Red and white afford attention to thermal aspects (it draws the attention and is the first thing the students refer to when using the IR cameras in sequence 2 and part C).

The specific numbers, the temperature values, afford measurement which is seen in the transcripts of the teacher students, that follow the decrease or increase of a temperature by stating the temperatures and how they go up or down (e.g. 36, 37, 38, 38.3, etc.).

Additionally the specific shapes or form of the IR cameras, e.g. the "smartphone" or "magnifying glass" form, has the affordance of spatial mobility which is made explicit in the teacher students' and instructors' use of the camera. The similarity to the camera function of a mobile phone may also invoke taking still images but this is not done by the participants in the two papers.

The relationship between the semiotic resources, the framing and the affordance can be summarized as:

Colors (red and white) → locally coherent activation of resources (warm, hot, fire, etc.) → conceptual framing (it is about heat or warmth) →affordance of attention to thermal phenomenon (it is red, warm, etc.)

Numbers (from minimum to maximum temperature possible for each situation) → locally coherent activation of resources (temperature, increase, precision, repeated attempts, etc.) → conceptual framing (temperature, increase) & epistemological framing (precision, repeated attempts) → affordance of measurement (35, 36, 37, etc.)

Form ("smartphone"/"magnifying glass") → locally coherent activation of resources (camera, smart phone, looking glass, etc.) → epistemological framing → affordance of spatial mobility (movement of IR camera and body)

The explicit reference to the color of red in Part C of Paper II and Sequence 2 of Paper I may, perhaps, be the result of both phenomena being novel to the students in terms of experience (the engineering students may not have seen or sensed deliquescence before and the teacher students may not have seen or sensed the transfer of heat to the paper put on the cup with water).

7.4.2 RQ2 & RQ3: Epistemological and conceptual framing

There are two levels of contextual aspects potentially affecting the framing: Large-scale aspects that affect the *epistemological framing* include the room and teaching situation that the participants act in, how problems/tasks are situated (everyday or disciplinary contexts, phenomenon discovered on their own or presented to them) and the experience or identity that they bring ("experts" and "novices") to this environment. The affect these aspects have on the framing can be identified in how the participants talk and how they act (answering "What am I to do in this situation?"). The other level of contextual aspects, affecting the *conceptual framing*, is a more fine-grained one that includes the semiotic resources of the IR camera, visual cues and the teaching material used (including the situations for each task), e.g. the sources for activating some resources in answering "What is this about?".

The two types of framing complete each other as the conceptual framing impacts what knowledge you apply to the situation and the epistemological framing affects how you apply it, i.e. your behavior. Consider the situation of walking down the street and noticing that the person in front of you has a wallet sticking out from his pocket, thus focusing your attention on the wallet. You would, hopefully, not think of stealing the wallet even though your conceptual framing tells you that the situation is about money, consumption and wealth. The reluctance to steal the wallet is caused by your epistemological framing, e.g. what you should do in the situation, which is affected by large-scale structures such as the norms in the society, your personal values about what is right or wrong behavior, etc.

RQ2: How do primary school teacher students, engineering students and instructors come to conceptually frame the situations that they are presented with for their investigations with IR cameras?

Perhaps the most prominent example of the students' conceptual framing is expressed when the engineering students get to observe deliquescence with the IR cameras to then explain it (sequence 2), or when the teacher students get to observe the paper being placed on the cup with water (part C) and both groups of students begin by referring to the semiotic resource of red which ends with an explanation of each phenomenon, given different amounts of time depending on the group of students. An example of the process of conceptual framing, in terms of semiotic resources and resources, is illustrated in *Figure 16*. After having framed the phenomenon to be about "warm", one student even mistakenly uses the word "heat" instead of "water" when formulating the explanation for the observation, potentially because "heat" is more closely associated to the established frame than water is.

The *conceptual framing* of the instructors is not made as explicit as in the case of the students, but it can be discerned through how they interact with the IR cameras while describing what they see: Instructor 1 begins by describing the aspect seen by the naked eye, that it has attracted a lot of water to then add that "…you clearly see the exothermic reaction" while holding the camera close to the experiment and keeping the gaze on the IR camera. As a response, Instructor 2 moves away his camera and prepares to interact with the container to move it (doing this generate a "heat trail" in the IR camera). Similar to the students' framing depicted in *Figure 16*, the instructors interpret the colors through *association* to *conceptually frame* the phenomenon to be about transfer of heat (which leads to the action of Instructor 2 moving the container), it is just that the colors are *appresent* for the instructors and the interpretation is automated compared to the students (one could perceive of the difference between the students and the instructors as if the former using *System 2* and the latter *System 1* (e.g. Heckler, 2011) in interpreting the semiotic resources). The result is that the instructors conceptually frame the situation in a similar way as the students (the resources activated in the framing may however differ so the conceptual framing should be slightly different).

The engineering students and instructors were presented with one phenomenon as one experiment. When including *several* experiments and anchoring situations relating to each experiment, like in the teaching sequence that the teacher students participated in, there is a risk in the students not relating each part to the other (if they all demonstrate some common knowledge). This may result in the students experiencing the physics as unrelated pieces of information that is not applicable to everyday life situations (which is an important goal with taking physics for the teacher students). In other words, there is a risk that the students find the sequence *incoherent* because of each part of the sequence being *conceptually framed* differently. However, the anchoring situations in the teaching sequence of Paper II, sitting in a sauna, stepping out from the shower and leaving a cup of water on table, were used in a productive way to conceptually frame the sequence as coherent. This is made visible in how they used the situations as productive resources in the meaning-making of the experiments (see *Figure 15* in chapter *6.2.4 Analysis and discussion).*

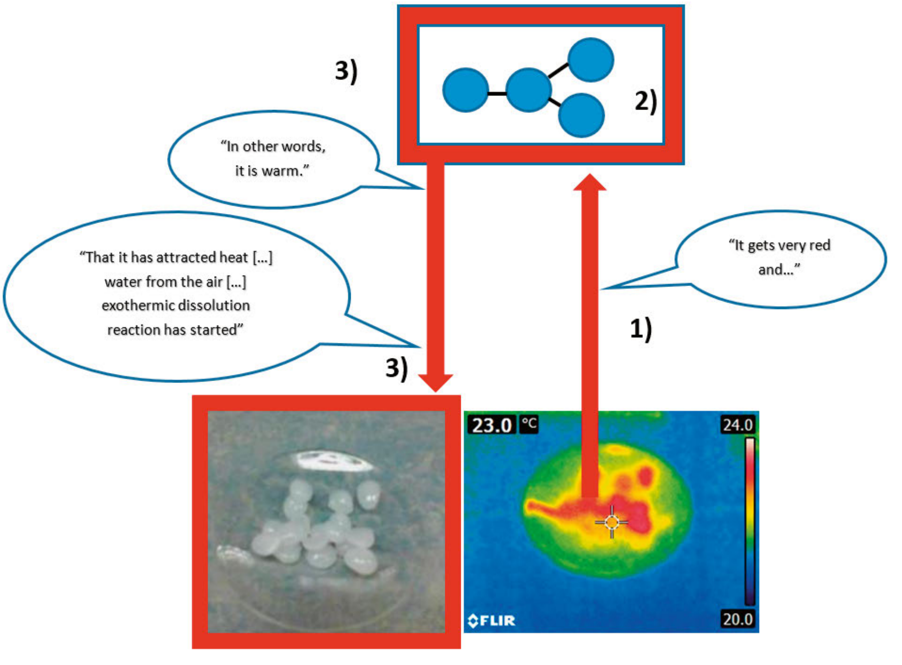

Figure 16. Conceptual framing of the engineering students while investigating deliquescence with IR cameras. 1) They begin by observing the phenomenon and focus on the semiotic resource of red which is 2) associated to one or several resources. 3) A conceptual framing emerges from the coherent activation of resources which is used to interpret the situation and that apply to the subsequent effort in explaining the phenomenon.

The *conceptual framing* in *Figure 16* depicts the *associations* of one individual, in reality though, there are two students involved and the conceptual framing is a joint framing through the individual activation of resources (and potential negotiation between the students about those resources). It seems to be quite straightforward in the case of the engineering students but it took *longer time* for the teacher students to come to a somewhat sound explanation, after having observed the heat transfer to the paper, potentially because more participants were involved in *negotiating* the resources employed in the situation in addition to the *epistemological framing* which was somewhat more *unstructured* and *inquiry-like* in the case of the teacher students.

RQ3: How do primary school teacher students, engineering students and instructors come to epistemologically frame the situations that they are presented with for their investigations with IR cameras?

Several large-scale aspects differ between the participants and affect the epistemological framing:

- **Experience:** The instructors are in the top regarding the level of *experience* of physics and chemistry with the engineering students at second place and primary school teacher at third place.
- **Identity:** The students have the *role* of students and the instructors have the *role* of teachers (and roles tied to their respective subdomain of physical chemistry).
- **Course:** The engineering students and instructors are part of a *course* where phenomena and content is supposed to be contextualized within the discipline, e.g. the experiments are supposed to demonstrate something they will encounter in their future profession. This is also true for the teacher students but the phenomena relevant for their future profession are everyday related phenomena that they can use to leverage their future primary school students intuition.
- **Room:** While the teacher students carry out the teaching sequence in a classroom, the engineering students and the instructors work in a chemistry lab.

All of these aspects have a potential impact on how the participants talk and act and so also how they epistemologically frame the situation. In addition, the IR camera may have contributed to the epistemological framing through two semiotic systems of the camera: the numbers and the form. Seeing a temperature value may strengthen the associations to “warmth” and “heat” (or “cold” and “freezing” depending on the temperature shown). But the semiotic system of numbers, of which the temperature values are semiotic resources, affect the epistemological framing through the affordance of measurement of the semiotic resources involved in the camera. This is made explicit in how the colors of red, white and blue seem to play a role in conceptually framing the phenomena when the teacher students use the IR camera, which is followed by the students stating the measurements of temperature as it increases or decreases (e.g. 29, 28, 28, 28.2, etc.). The form plays a similar role through the cameras specific form or shape which has the affordance of spatial mobility for the teacher students and instructors that actually use the IR camera in a dynamic way. The form thus add to the epistemological framing for these two cohorts.

Similar to the epistemological framings of "keeping to instructions" and "instant inquiry" found by Haglund, et al. (2015) among upper secondary technology students using IR cameras to investigate thermal phenomena, I have found two types of epistemological framing made visible through the actions and talks of the participants: *inquiry* (characterized by dynamic investigation and exploratory talk) and *instructed* (characterized by restrained investigation and cumulative talk) practice. The high level experience participants (the instructors) use *cumulative talk* during observation and exploratory talk during their explanation, but they *manipulate* the experiment and equipment to a higher degree than both the teacher and engineering students, i.e. they explore the phenomenon to an extent that is above what is required to give a sound answer through the "instructions" (the main questions in what they observe and how they would explain it). I would interpret this as an *inquiry* type of epistemological framing. In contrast, the engineering students did not interact with the experiment, kept the gaze on the cameras, upheld a static posture and used cumulative talk in both observing and explaining the phenomenon. This is the *instructed* type of epistemological framing. The teacher students used cumulative talk mainly during observations with IR cameras and exploratory talk mainly during their explanations (of the experiments in addition to the situations). Their postures were static by design (as they sat down around tables) but they moved around the cameras and investigated other thermal aspects than the ones present in the experiment (for example the temperature of their toes). Additionally, they manipulated some of the experiments (by pouring water on the table for example). The teacher students thus used mainly the *inquiry* type of epistemological framing in their investigation.

There is a risk in rating the two types of epistemological framing; that inquiry would be more fruitful than the instructed type. However, both types of epistemological framing seem to have their advantages and disadvantages in terms of making meaning of the presented phenomena: For the students, the instructed type seems to lead to a more structured investigation, e.g. the engineering students give a brief description which leads to an explanation without encountering any barriers distracting the reasoning on the way. This is also a result of the students having formulated hypotheses in a structured way during sequence 1. The inquiry type of epistemological framing leads to the teacher students encountering several barriers that may result in incomplete and overall fractured explanations (e.g. it is more difficult to pinpoint a final and correct explanation in the case of the teacher students). On the other hand, inquiry may also lead to more insights and a fuller description about the phenomenon, for example discovering thermal conduction to the table in the case of the instructors, or that water on a hand evaporate causing the hand to feel cold after having had steam condensating onto the hand (part A in Paper II).

Imagine if the target for some teaching is thought of as an actual *target* (*the teaching target*), like the target in *Figure 17*, where the most outer ring is just good enough and the explanations get more fine-grained as they move towards the middle. The instructed type would then quickly come to the outer ring of the target, e.g. it is structured and fast but just good enough. Inquiry takes a longer time (the case for both the teacher students and the instructors after the initial "basic" explanation) but may end with a more fine-grained explanation, e.g. closer to the middle of the target, as more ideas are tested and the situation is looked at in new ways (e.g. manipulating the experiment or other ways of changing the way one looks at the phenomenon). Inquiry may, however, also lead to other targets (other than the teaching target) that may result in new insights that would not have been the case in instructed type of epistemological framing (this new knowledge may also just be irrelevant to the teaching unit though).

The *epistemological framing* of the instructors, which is *structured* and of the *inquiry type* does not lead to any encounters with barriers but give a deeper explanation through the inquiry pushing the reasoning into a more fine-grained one (i.e. the inner ring of the target). This is kind of what *ISLE* (e.g. Etkina, Planinšič, & Vollmer, 2013) is trying to do for students: *scaffolding* the structure so that the *epistemological framing* is *structured* while keeping the *inquiry type*.

Figure 17. Target for teaching. The most outer ring is just good enough and each subsequent ring towards the middle are more fine-grained explanations. Getting to the outer ring is quick through instructed type of epistemological framing but inquiry type of epistemological framing may get to a more fine-grained explanation, e.g. closer to the middle.

7.4.3 RQ4: Barriers and productive resources

RQ4: How can resources support or hinder meaning-making and reasoning for undergraduate students and instructors investigating one or several thermal phenomena?

Different resources have different purposes, for example, some resources may be productive in relating situations and contexts in a way that it is experienced as coherent (through conceptual framing), like the shower, the sauna and the cup with water (see *Figure 15*, in *6.2.4*). These resources may, in addition to creating a sense of coherence, be productive in pulling back reasoning from a barrier, as illustrated in *Figure 15*, in *6.2.4*. The teacher students were distracted by an empty cup acting as a barrier (the resources associated to the empty cup were really the barriers) which made them reason about how "something" would go from the paper to the empty cup (rather than water evaporating from the paper).

Other *distracting barriers* can be found in the engineering students' initial encounter with the deliquescence in sequence 1 (Paper I): The glossiness of the salt leads them to explain it as "melting" which they originally contribute to the temperature in the room and then to the light exposure. The associated resource of "melting" is in this case the actual barrier (the glossiness, and perhaps other surface features of the salt, is associated to melting). However, the engineering students move on by adding another, alternative, explanation (residual water as a barrier; another association to what is observable) which misdirects the reasoning again, but this is resolved by the students' associations to a preparation bench in a lab (it is supposed to be kept clean for the preparation materials) which acts as a productive resource in this case to push them towards yet another explanation (the salt attracting water from the air). They hardly encounter any barrier in sequence 2 as they have negotiated the explanations in sequence 1 already (one of the students mistakenly uses "heat" instead of "water" for the explanation, in line 7, sequence 2 of Paper II, but this is resolved almost immediately).

The mentioned barriers are all *minor* in that they occur one or a few times in the reasoning process. In contrast, a (*major*) barrier encountered several times in the teaching sequence is the second law of thermodynamics, often combined with or informing the resource of "heat rises", which paradoxically has earlier been shown to be a barrier to heat transfer (Clough & Driver, 1985). These barriers not only distracts reasoning but hinders the access to the concept of condensation (see, for example, analysis for Paper II in *6.2.4*).The second law of thermodynamics acts as a *barrier* in another of their explanations: The sensation of cold when walking out from the shower (when mentioned during part A). One students asks why it feels colder and the others respond that it has to do with the temperature in the hand increasing by showering, thus resulting in a higher difference in temperature between body and environment.

They compare it to walking out from a cold environment (a cave) to a warmer environment (outside of the cave) or the increased body temperature of walking uphill and then relate it to the second law of thermodynamics (energy "wants" to be distributed equally). An explanation involving evaporation and heat transfer is later given when encountering the experiment involving the same phenomenon in part B.

The instructors do not seem to get distracted or hindered in their reasoning by any barriers. Each added resource pushes their explanation toward a more refined explanation, i.e. the resources they use are productive. This may be a result of their *structured*, yet *inquiry type* of practice (as a result of the *epistemological framing*).

The shower, the sauna and the cup of water are all productive resources in terms of relating several experiments and situations to each other to form coherence and "filter out" the relevant aspects, e.g. evaporation, condensation and heat transfer (it was mainly evaporation that was used in explanations by the students but they did at times use condensation). The threads tying the parts together are illustrated in *Figure 15*.

Additionally, red (and white) in the IR camera, and at times, the numbers (temperature values), support the reasoning in a productive way and seem to push the reasoning forward. For example, when both the engineering students and the teacher students use "red" (and "white" in the case of the engineering students) to conceptually frame the situations presented to them (see RQ3). Blue is explicitly used to for crosschecking, like when one of the teacher students says "The table became colder" and another teacher student responds "The water is dark blue" or when a student asks if the water is warmer than the table and another responds "Is the table blue?". However it is difficult to tell how the colors are used by the instructors as they never explicitly refer to them but as they do generate "trails of heat" caused by the thermal conduction when moving the container with salt, they do *use* red in a productive way in their investigation.

8. Contributions and implications

The result of my research is the result of my, and my co-authors', interpretation. Any implications should be read in the light of this. A couple of implications can be drawn from my research:

8.1 Theoretical contributions

Adding to the constructs of the Resources framework, I have proposed the concept of *barriers* as a way to emphasize the resources that hinder or distract productive reasoning. Resources are either productive or not productive, however, as I have found in my literature review and my data, some resources may not only be neutral in regards to some learning but actually hinder some reasoning by halting the reasoning, or drawing away the attention from aspects that are relevant to the goal of the teaching. Barriers has thus been offered to term those resources that draw the attention away from the goal of the task or teaching unit that the learners participate in, or hinder the access to a productive resource. The barriers are often resources associated to some irrelevant aspects (for the *context* and *teaching target* of the teaching situation that the learners participate in) that become the focus of the learners' attention.

As seen in the analysis and synthesis of the two papers, the factors that affect *framing* can be discussed at different levels of "grain-size", similar to how Redish (2014) described different grain-sizes of knowledge structures (psychological models, social cultures etc.) in his *grain-size staircase*: The more coarse "grain", or macro factor, affecting the *epistemological framing* of a situation, could for example be types of contexts, e.g. the everyday context of some tasks. A context is itself a combination of many "smaller grains" or micro factors that contribute to the experience of the context. These micro factors could be what has been referred to as *semiotic resources* (or visual cues as a subcategory of some semiotic resources belonging to semiotic systems that afford visibility), e.g. "red" as a semiotic resource, an object like the empty cup or a specific everyday situation such as the sauna can all be associated to a *resource* that can be a *barrier* or a *productive resource* and lead to a *conceptual framing* of the situation. There is thus a relationship between the concepts of *resource* and *framing* from the Resources framework and *semiotic resources* from the framework of Social semiotics: as framing "corresponds to locally coherent activation of resources" (Hammer et al., 2004, p. 5) and the semiotic resource of red has an associative value that relates to heat (Kress & van Leeuwen, 2002). Again, there is a link between the *semiotic resource* and a *resource* through association which adds to the *framing* (every observation with IR cameras begins with an image of colors).

The IR camera seems to encourage *cumulative talk* as it is a tool for gathering data and observing phenomena. Considering the cameras as technical lab equipment, this aligns with the results of Andersson & Enghag (2017). In addition, the IR camera stabilizes the reasoning about thermal phenomena in that it focuses the talk on heat. When reasoning trails off from the subject of learning, the IR cameras can refocus the reasoning to move back to the main path of reasoning toward the learning target.

8.2 Methodological contributions

- While exploratory talk seems to indicate a negotiation of individual resources towards an agreed conclusion, cumulative talk can indicate individual resources mapped to observations to make explicit readouts. The types of talk could, depending on the disciplinary experience of the participants, be used as an analytical tool in analyzing how participants *epistemologically frame* the activity they are currently undertaking in a laboratory practice. For example, students engaged in cumulative talk would have framed the situation as one where the aim is to collect and gather data while on the other hand, students engaged in exploratory talk frame the situation as one where knowledge is to be negotiated and pieces of knowledge are to be linked to form hypotheses and/or explanations. This seems to be the case for undergraduate students with varied experience of science. For a bigger leap in disciplinary experience, that is researchers in the field or rather instructors of those undergraduate students, it is less obvious how they frame an activity by just analyzing the type of talk engaged in (additional information, on for example, their actions are needed in this case).
- In vivo towards in vitro: The two papers provide an example of a transitioning process between *in vivo* and *in vitro* studies (Dunbar & Blanchette, 2001) as Paper I is placed within the participants' natural course practice and the studied phenomenon emerged out of that naturalistic context. Paper II had a designed structure but the context followed the course that the participants were enrolled in (e.g. the setting was naturalistic). As such, Paper II is not really a full in vitro study but rather a step away from an in vivo study (or a step towards an in vitro study depending on how one looks at it). Dunbar & Blanchette (2001) propose that in vivo studies are used to *generate hypotheses* that can be tested in in vitro studies. As neither of the two papers are

a full-fledged in vitro study, Paper I and II generate hypotheses rather than provide confirmation or disconfirmations of hypotheses.

8.3 Teaching and learning

- The dual *affordance* of IR cameras, as both disciplinary and pedagogical tools, make them apt for bridging disciplinary practice with learning of some content relevant for that practice, in this case heat transfer. The IR cameras could provide a basis for discussions involving both students and instructors, from both chemistry and physics.
- When designing tasks or problems for a certain physics content, it is important to consider how *close the contexts* of each problem are to the other problems. A too large gap between the contexts may lead the students to frame the learning situation as incoherent and incomprehensible.
- It is productive to start in what the learners have experienced to then move toward a more experimental approach to the same phenomenon.
- A good start for learning more about heat is to get learners to talk about heat-related phenomena. The *semiotic resources* of IR cameras are initiators of reasoning processes on thermal phenomenon through affordances such as attention (the colors can filter out irrelevant aspects), measurement and spatial mobility. They also seem to refocus discussions when they seem to trail off from the task at hand. In this sense, if the goal of some teaching unit or sequence is to learn more about heat then give the students access to an IR camera and provide the appropriate teaching material in accordance with the level of education of the learners.
- Like the IR cameras, *embodied experience* can also function as an initiator to reasoning about heat transfer. It seems, however, that resources related to embodied experience may also act as *barriers* to reasoning about phase transition.
- It is important to have both *cumulative* and *exploratory talk* in mind when planning a lab activity as they are both just as important: cumulative talk builds a body of knowledge that can be negotiated through exploratory talk to reach an agreement on some explanation. This can be done by for example including both a part on experimentation and data collection, and a part on more conceptual questions to attend to both the short-term goal of a lab (e.g. calculating a value) and the more long-term goals (e.g. learning more about a specific concept or linking multiple concepts). POE can be a useful method for encouraging both cumulative and exploratory talk.
- To encourage a *structured inquiry type of epistemological framing* similar to the framing of the instructors, one could use analogies and

examples to support the structured reasoning of students or propose experiments to test their ideas in a structured way (Robertson et al., 2019) similar to the method of *ISLE* (e.g. Etkina, 2015) which is described in *5.2*. ISLE could thus be another option in supporting the type of structure that seems to be missing in the teacher students' investigation.

9. Future research

I have already initiated my next study (C. R. Samuelsson et al., 2019) which is a more detailed study on the *resources* used when reasoning about a thermal phenomenon involving phase transition. I intend to add the concept of barriers to the set of resources analyzed (prototypes, exemplars, heuristics, p-prims and potentially threshold concepts (Meyer & Land, 2003)) to get a theoretical tool to describe the distractors of reasoning processes.

The upcoming study involves multiple groups of students that reason about the same phenomenon. If one plots the reasoning of each group as reasoning paths in which nodes represent the resources employed in the reasoning and the edges (links) represent the associations made between the different resources it should be possible to find the barriers that distract the reasoning and resources that are productive in directing the reasoning back to the main path. This can either be done through *quantitative network analysis* or *qualitative network analysis* (Bruun, Lindahl, & Linder, 2018) depending on the detail of the analysis and the amount of data available. In doing this it is also possible to identify threshold concepts (Meyer & Land, 2003) that act as gateways to a broader range of skills or knowledge, for example the concept of limit in mathematics which is fundamental in learning about calculus.

Another topic that would be interesting to study further is the topic of *epistemological framing* and the resources that affect that specific type of framing. I would have hypothesized that the resources affecting epistemological framingare larger structures like culture and identity or that the framing is emergent from many more fine-grained structures such as constellations of semiotic resources. However, from the researche presented in this thesis, it seems that few semiotic resources may have an impact on the epistemological framing, e.g. the form of the IR camera and the temperature values provided in the situation affecting the participants' talk and actions. Perhaps this could be attributed to the semiotic systems rather than the specific semiotic resources in that the system of numbers activates some set of resources that relate to accuracy and precision, and the general form of lab equipment activate some set of resources related to investigation and research.

In addition, it would be interesting to explore the so-called *teaching target*, or purposes of a teaching unit, more. Especially in how students perceive of the purpose. This has to some extent already been done in an ongoing study that, together with the more detailed study on reasoning, are meant to be included in my final doctoral thesis.

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Appendix A

Consent form, Paper I

UPPSALA
UNIVERSITET

Medgivande för studie kring användning av värmekameror som pedagogiskt hjälpmedel

Som en del i den pedagogiska utvecklingen av laborationer i kurser i kemi vid Uppsala universitet vill vi genomföra en forskningsstudie kring hur man kan använda värmekameror vid öppna laborationer i termodynamik.

Syftet med studien är att undersöka hur värmekameror influerar vad studenter uppmärksammar och hur de eventuellt kan stödja förståelsen av ämnet. Data kommer att samlas in genom videoinspelning av det laborativa arbetet, och fotografering av arbetsmaterial, t.ex. era anteckningar.

Deltagande i studien är helt frivilligt. Du kan när som helst under studien välja att hoppa av.

Insamlad data kommer att analyseras av oss i forskargruppen, t.ex. genom att skriva ut och tolka vad ni säger, och kan presenteras på konferenser och i vetenskapliga artiklar, men inte i andra sammanhang, såsom sociala medier. Ditt namn kommer inte att nämnas, för att garantera anonymitet.

Tack för Ditt deltagande!

Robin Samuelsson, Jesper Haglund och Staffan Andersson, Institutionen för fysik och astronomi, Maja Elmgren, Institutionen för kemi – Ångström

Om du vill veta mer så hör gärna av dig till oss på robin.samuelsson@physics.uu.se eller maja.elmgren@kemi.uu.se.

Jag ger mitt medgivande till deltagande i den vetenskapliga studien.

Underskrift:____

Namnförtydligande:__________________________________

Consent form, Paper II

UPPSALA UNIVERSITET

UPPSALA UNIVERSITY PER

Medgivande för projekt kring lärande i termodynamik och användning av värmekameror som hjälpmedel (Lärande och undervisning i termodynamik)

Projektets syfte och vad deltagandet innebär:

Syftet med projektet är att undersöka lärande inom värmelära och termodynamik, samt hur värmekameror influerar vad studenter uppmärksammar och hur de eventuellt kan stödja lärande i värmelära, termodynamik och angränsande områden. Detta kommer att studeras genom att ni får delta i en lärandesekvens.

Data kommer att samlas in genom videoinspelning av det laborativa arbetet, och insamling av eventuella anteckningar.

Insamlad data kommer endast att analyseras av oss i forskargruppen, t.ex. genom att skriva ut (transkribera) och tolka vad ni säger och gör. Foto- och videodata kommer ej att visas för någon annan än oss forskare. Bearbetad data (transkripten) kan komma att presenteras på konferenser och i vetenskapliga artiklar, men inte i andra sammanhang, såsom sociala medier. Ditt namn kommer aldrig att nämnas i något sammanhang, för att garantera anonymitet.

Deltagande i projektet är helt frivilligt. Du kan när som helst under, eller efter, projektet välja att hoppa av, i enlighet med Dataskyddsförordningen, genom att meddela detta via mailadressen längst ned i dokumentet.

Om vi skulle vilja använda data på ett annat sätt kontaktar vi dig för ett utökat tillstånd.

Tack för ditt deltagande!

Christopher Robin Samuelsson, doktorand vid Fysikens didaktik,

Institutionen för fysik och astronomi, Uppsala universitet

- ☐ Jag har läst det medföljande informationsbladet för projektet Lärande och undervisning i termodynamik samt blivit informerad muntligt om deltagandet.
- ☐ Jag ger mitt medgivande till att video- och ljuddata, samt eventuella anteckningar, samlas in under mitt deltagande i projektet.
- ☐ Jag tillåter endast de forskare och forskningsgrupper som omnämnts i informationsbladet att ta del av insamlad rådata.
- ☐ Jag förstår att publicerad data, såsom forskningsartiklar, rapporter och konferenspresentationer, ej kommer att kunna användas för att identifiera mig.
- ☐ Jag har förstått att jag när som helst kan dra mig ur projektet och att rådata som inkluderar mig då kommer att förstöras.

Jag ger mitt medgivande till deltagande i det vetenskapliga projektet.

Underskrift:______________________________________

Namnförtydligande:________________________________

Mail: ____

Om du vill veta mer så hör gärna av dig till robin.samuelsson@physics.uu.se

Appendix B

The major steps of the transcription process for Paper I.

1) Initial observations (after viewing the video recordings)
M2U00379
Studenterna hade redan tidigare märkt (finns dokumenterat i M2U00370) att natriumhydroxiden ”svettas” (de säger att den smälter) och gissar på att det kan bero på ljusexponering, vattenrester (att det ej var torrt i burken) men avslutar med att det kan vara vatten i luften. När vi sedan gjorde själva försöket skrattar en av studenterna bekräftande (första minuten i M2U00379) när de ser fenomenet i värmekamerorna och den värmeökning som då skett.

2) Initial transcripts (all data was transcribed at this stage)

Robin: Hur går det?
Student 6: Det går bra, vi har mätt upp saltet nu och eh...dock är jag lite intresserad utav det för att efter en liten stund, jag vet inte om det går att se så det börjar smälta nästan. Det är kladdigt.
Robin: Mm, vad tror du det beror på?
Student 6: Jag vet inte riktigt för att det är ju...Ah! okej! Om det inte har med, vad heter det, temperaturen s¨kanske det har att göra mde ljusexponering eventuellt men...
Student 5: Tror du inte att det är vattenrester som löser upp sig?
Student 6: Ja, det kanske det är! Men jag hade för mig att det skulle vara torrt det som är där...[tittar bort mot bänken med labmaterial] men hmm, möjligen....

3) Structuration of transcript in different themes (phenomenon and/or theory

Grupp/Tema	<u>”Svettande” NaOH</u>
Student 5 & 6 **(Video: 370)**	Robin: Hur går det? Student 6: Det går bra, vi har mätt upp saltet nu och eh...dock är jag lite intresserad utav det för att efter en liten stund, jag vet inte om det går att se så det börjar smälta nästan. Det är kladdigt. Robin: Mm, vad tror du det beror på? Student 6: Jag vet inte riktigt för att det är ju...Ah! okej! Om det inte har med, vad heter det, temperaturen s¨kanske det har att göra mde ljusexponering eventuellt men... Student 5: Tror du inte att det är vattenrester som löser upp sig? Student 6: Ja, det kanske det är! Men jag hade för mig att det skulle vara torrt det som är där...[tittar bort mot bänken med labmaterial] men hmm, möjligen....

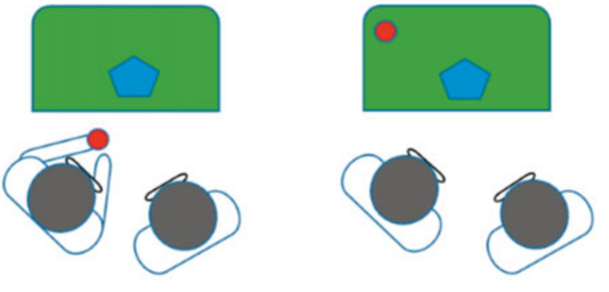
4) Multimodal categories added

Student 5			Student 6			Robin		
Speech	Motor skill activity	Sensory activity	Speech	Motor skill activity	Sensory activity	Speech	Motor skill activity	Sensory activity
						Robin: Hur går det?		
			Student 6: Det går bra, vi har mätt upp saltet nu och eh...dock är jag lite intresserad utav det för att efter en liten stund, jag vet inte om det går att se så det börjar smälta nästan. Det är kladdigt.	Points at the container with NaOH Picks up the container with NaOH. Points around the NaOH. Swipes finger over the glas and rubs fingers.				

Transcriptionline	Interlocutor	Swedish speech	Translated speech	Body	Interaction with artefacts	Gaze	Comment	Allmänna kommentarer
1	Researcher	Hur går det?	How is it going?					Alla semiotiska resurser beskrivs via studenterna, inte forskarna. Dvs. en viss posture som beskrivs på en rad där forskaren talar, utförs av studenterna, inte forskaren.
2	Student 6	Det går bra, vi har mätt upp saltet nu och eh...dock är jag lite intresserad utav det för att efter en liten stund, jag vet inte om det går att se så det börjar smälta	Fine, we have weighed the salt now and ehm...though, I am a tad interested by it since after a while, I don't know if it is visible, it is kind of melting. It's sticky.	Turns towards the researcher after picking up the watchglass to show the findings.	Picks up the watchglass. Points around the NaOH when saying "It's starting to melt". Rubs fingers when saying "It's sticky"		Studenternas diskussion centreras runt det denne har hittat genom att hen flyttar själva fenomenet till en position där alla deltagare står runt det. Till skillnad från vid användande av värmekamera då	Studenterna har statiska postures hela tiden om inte annat nämns i Body-sektionen

6) Adapting the transcripts for publication and adding illustrations (line 2 and line 4 illustrated below)

LINE	INTER-LOCUTOR	VERBAL ACTION	NON-VERBAL ACTION
1	Researcher	How is it going?	
2	Student 2	Fine, we have weighed the salt now and ehm... though, I am a bit interested by it since after a while,…	Picks up container with salt from the bench.
		I don’t know if it is visible it is kind of melting.	Points around the salt.
		It’s sticky.	Rubs fingers.



7) The published transcript, adapted for the format of the journal which the paper was published in, can be found in Paper I

Appendix C

The analyzed data is available on DiVA (Dataset Hot vision, Samuelsson, Elmgren & Haglund, 2016):

Identifikatorer
URN: urn:nbn:se:uu:diva-406298
OAI: oai:DiVA.org:uu-406298
DiVA, id: diva2:1412586

Appendix D

The analyzed data is available on DiVA (Dataset Going through a phase, Samuelsson, Elmgren, Xie & Haglund, 2018):

Identifikatorer
URN: urn:nbn:se:uu:diva-406300
OAI: oai:DiVA.org:uu-406300
DiVA, id: diva2:1412591

Appendix E

The analysis for the synthesis (of talk, resources, information used and body positions)

Data ***("correct")***	*Initial attention*	*Talk*	*Center of ecological huddle*	*Information shared/cumulated*	*Reasoning/ Resources* ***barrier***
P1Seq1 (ob, ex & pr)	Visual cue (melting) → sensation (sticky)	Explorатory	Phenomenon, break when no confirmation	Naked eye (sensation) Naked eye (gestures)	Melting Stickiness **Exposure to light** **Residual water** The cleanness of the preparation bench Air Water vapor Ventilation Dissolving Heat
P1Seq2 (ob & ex)	(Laugh) Red → white	Cumulative	Around IR cameras and phenomenon	Thermal/(sensation)	Red White Warm Water in air Exothermic reaction
P1Seq3, ob	Observation of condition of salt (sticked together) with naked eye →Observation with IR camera (close to salt)	Cumulative	Around IR cameras and phenomenon. Break to gather visual information and combine with thermal images.	Naked eye thermal Naked eye (gestures)	Scooping as indicator for quality NaOH Hygroscopic Exothermic reaction Heat transfer to table and surroundings IR cameras Water on/around salt
P1Seq3, ex	NaOH dissolves in water	Exploratory	Around IR cameras and phenomenon.	Naked eye thermal Naked eye (gestures)	NaOH Solution Absorbing water from air

	→ Challenged		Break to gather visual information and combine with thermal images.		Hydrating Crystal structure Disciplinary identities
P2Sauna	Vaporization of water on rocks → heat rises	Exploratory	Static by design	(Sensation)	**Sweating** Sounds of water on hot rocks Heat goes up Warm body Culture Energy transfer Condensation Evaporation Gas → liquid on body (Northerner/Finish) **Insulation/coat**
P2KettlePr	Hot → memory of boiling water	Exploratory	Static by design	(Sensation) Naked eye (gestures)	Boiling water and burn Sauna and burn Gas goes up SLT Energy transfer Moisture/wetness
P2KettleOb	Looks hot → temperature values	Cumulative	Static by design	Thermal Sensation Naked eye	Warm hand Numbers Wetness Shower
P2KettleEx	Confirm hypothesis →expand shower example	Exploratory	Static by design	(Sensation) Naked eye (gestures)	Shower Warm body Heat transfer Condensation Dancing molecules Liquid molecules slower (kinetic) SLT (cause condens) Body temperature Cave excursion Walking uphill Laws of thermodynamics
P2Shower	Feels cold → movement of air	Exploratory	Static by design	(Sensation) Naked eye (gestures)	**Wind** Shower **Closed and open bathroom** **Time of showering** **Temperature of water**

P2Sprinkle, Pr	Formulate hypothesis → it gets cold	Explorative	Static by design	(sensation) Naked eye (gestures)	Cold body Room and body temperature Water used for baking Heat transfer
P2Sprinkle, Ob	Ask for sensation → experienced and observed as cold	Cumulative & Explorative	Static by design	Sensation Thermal Naked eye	Cold hand Evaporation Temperature Color Humidity Evaporation in glass of water Boiling point Wind Temperature of toes
P2Sprinkle, Ex	Colder when water added to table → the water is dark blue	Cumulative & Explorative	Static by design	(sensation) Thermal Naked eye (gestures)	Color Paper absorbing water
P2Cup and paper	Evaporation for the current temperature of the room → add a paper and evaporation continues while paper gets wet	Explorative	Static by design	(thermal) Naked eye (gestures)	Evaporation Teaching in course Wet paper crumbling **Cooking lentils** Breathing paper Painting with water Glass of water on bedside table Hand above kettle Archived papers (school grades) and moisture Net energy IR camera
P2 Water in cup, Ob	(Asked to look at value by researcher) Temperature → temperature	Cumulative	Static by design	Naked eye Thermal (sensation) Naked eye (gestures)	Temperature Sprinkle water on skin Evaporation Humidity Heat Energy **Second law of thermodynamics**
P2Paper on cup, Ob	Red → warm	Cumulative	Static by design	Thermal Naked eye	Color Temperature Measured temperature of water

P2Paper on cup, Ex	Heat rises → insulation	Cumulative	Static by design	Thermal Naked eye (gestures)	Heat Insulation Temperature
P2Move paper, Pr	Heat moved to another cup → that cup will become warmer	Cumulative	Static by design	Naked eye	**Empty cup** Heat as substance
P2Move paper, Ob	Temperature → colder	Cumulative	Static by design	Thermal Naked eye (gestures) Naked eye	**Empty cup** Temperature
P2Move paper,Ex	Water disappeared → condensation	Exploratory	Static by design	(sensation) Thermal Naked eye Naked eye (gestures)	Sauna Shower Condensation Dripping water Evaporation Energy transfer Cold Heat

Explanations:
(sensation) – refer to sensation without actually having it
Sensation – refer to sensation and "feeling it"
(Thermal) – refer to thermal information without having access to it
Naked eye (gestures) – they attend to some gestures made by one or multiple participants
SLT – Second law of thermodynamics

The talk can be summarized as:

	E-students	**T-students**	**Instructors**
Cumulative	**Ob, ex**	**KOb, SpOb*,SpEx*, WCOb, PCOb, PCEx,** MPPr, **MPOb,**	**Ob**
Exploratory	Ob, ex, pr	Sa, KPr, **KEx,** Sh, SpPr, **SpOb*, SpEx*,** CP, **MPEx**	**Ex**

Bold – with IR camera
K – kettle
Sa – sauna
CP – cup and paper
PC – Paper on cup
WC – water in cup

MP – Move paper
Sh – shower
Sp – sprinkle water
* the observations and explanations for these parts were not as clear as for the rest of the teaching sequence

Analysis of the teacher students' reasoning paths:

The reasoning paths presented below are to be read in the light of this as the negotiated paths throughout each part of the sequence:

- **A: Sauna** – Vaporization of water on rocks → heat rises → condenses on body → energy from vaporization transferred → we feel warmer

This explanation was complicated by one of the students adding the resource of insulation (the water act as insulation like a coat which makes it feel warm). The increased humidity in the sauna leads to steam condensing on our bodies and our sweat can not cool down our bodies which could be interpreted as "insulation" as the added water on our skin keeps some of the heat that could have been transferred in the evaporation process of the sweating. The reasoning is in this sense not too farfetched and did not hinder the explanation of energy transfer from the steam to the body during the phase transition of the water.

- **A: Kettle, prediction** – water as gas → contact with hand → transitions into liquid → energy transferred → heats hand → gets wet
- **A: Kettle, observation** – it gets warm → temperature readings → it feels wet → it feels cold → like stepping out from the shower
- **A: Kettle, explanation** – confirm hypothesis → shower → body heated → condensation → fast and dancing molecules → transfer energy to the hand → hand colder than the steam → molecules slow down → condensation → shower → surroundings lower temperature than body after shower → experienced as cold → memory of cave excursion → cold outdoors experienced as warm after being in an even colder cave → walking uphill cause for it feeling warm outdoors → difference in temperature between hand and steam experienced as warm → experienced as cold after steam has condensed on hand → heat is transferred → second law of thermodynamics

The students are here quite early with some productive reasoning which they later relate to the situation of stepping out from the shower. After they have observed the experiment with the kettle they explicitly state that they now have confirmed their hypothesis which is explained as the body being heated as a result of condensation transferring energy to the hand.

The transfer of energy is elaborated further with a type of kinetic model (molecules move fast in the gas phase and they lose some of their energy to the hand upon contact which makes them move slower). In addition, they return to the situation of the shower and try to explain it through the second law of thermodynamics in that the experienced warmness or coldness is a result of a temperature difference between their bodies and the environment (which in this case does not involve phase transition).

- **B: Shower** – it feels cold → air moves → warm if door is closed, cold if it is open → less cold if door is open during shower → it gets cold if the room is small and you walk out the door → temperature as a substance which moves together with air → cause for feeling cold during windy days → heat transferred to surrounding air and moved away from body in shower → body transfers more heat to surroundings → colder after taking a shower compared to before because the body has a higher temperature → warmer after taking a cold shower → heat is moved out from the room if the door is opened → it feels cold → second law of thermodynamics → difference in temperature

The students had a longer discussion giving arguments and counter-arguments, on whether it would feel cold or not when stepping out of the shower. Some students tried to follow the instructions and discuss how it felt when stepping out from shower curtains and the others wanted to add the aspect of having the door opened or closed. At one occasion, one of the students even stated that a better situation to discuss would have been taking a shower in a small bathroom and opening the door to step out from the room (which is analogous to the space behind the curtains and the curtains acting as the door in the situation presented to them). The shower curtain would essentially function as a "door" and keep a temperature gradient between behind and outside of the curtain, the students did not make this link, however. The door seemed to shift their reasoning in a way that the situation became more difficult to explain than it had to be, almost as if the door acted as a barrier in their reasoning.

The final explanation was based on the second law of thermodynamics and how bodies in (warm) showers increase in temperature which makes it feel cold when stepping out from the shower if the body has a higher temperature than the surroundings. In contrast, taking a cold shower which lowers your body temperature, will result in an experience of warmth when stepping out from the shower. The explanation did not really touch upon the phase transition of evaporation but did rather revolve around heat transfer from body to air and vice versa.

- **B: Sprinkle water**, **prediction** – aim at formulating hypothesis → it will get cold as water of room temperature is lower temperature than our bodies → water used for baking does not feel at all → the water will feel cold and heat will transfer from the body → it would not have been felt at all if the water would have been same temperature as the body

The students seem to apply the second law of thermodynamics to the task of predicting the outcome here as the difference in temperature between water and body seem to play a big role in their reasoning. Their hypothesis, that it will get cold and heat will be transferred, is a step toward an explanation, but they have yet to add phase transition in the reasoning of this part of the sequence.

- **B: Sprinkle water, observation** – feels cold → visible that it is cold → low temperature of hand → it will be cold until the water has evaporated → relate to sweating and humidity →water in a glass will evaporate → boiling point is not required for water to transition into gas → movement of air adds to it feeling cold → hand is green → temperature readings → sensation of cold → sensation of warm → cold fingers → experience of cold or warm depend on change in temperature → toes are cold
- **B: Sprinkle water, explanation** – cold when water is sprinkled on table → dark blue → evaporation → the water will disappear given time → green → suggestion on observing water sprinkled on paper

The students make use of both embodied experience and the semiotic resources of the IR cameras to reason about the phenomenon and add phase transition to their explanations. They use sweating and water in a glass as resources to argue for the evaporation of the water that has been sprinkled on their hands and arms.

The students observed and tested new ideas while explaining the initial phenomenon which leads to the structure alters between observation and explanation in this section of B. It seems that their talk also altered along with these shifts.

The students concluded the part by sprinkling some water on the table and offered a similar explanation to sprinkling water on the arm to this new variant of the experiment. They ended the experiment by saying that it would be interesting to observe water being absorbed by some paper, which foreshadows the experiment in part C.

- **C: Cup without and with paper, prediction** – evaporation in current temperature → paper gets wet if added → evaporation faster without than with paper → analogy to cooking green lentils and adding a plate which gets wet when covering the cooked lentils → paper should crumble because of the water → too slow process to wet the paper to that extent → water moves through the paper as it “breathes” → the paper will not get wet to the extent that it falls apart → the water dries when painting with water → steam could have crumbled the paper but not water vapor → the paper do not "stop" the water → hand over kettle → archived papers fall apart by moisture from the surrounding air → balance between air drying and water wetting the paper → temperature will increase when paper is added → nothing happens if the energy transferred to and from the paper is equal → if more energy is transferred to the paper than from the paper → increase in temperature → evaporation carries energy which will end up heating the paper → transition from liquid to gas results in heating the paper →should be a change in temperature

Initially, the students almost get stuck with the discussion on whether the paper would get wet enough to fall apart or not. There are multiple competing resources that confuse the students: The paper does not fall apart when painting with water but enough water for the students to believe that it would destroy a thin sheet of paper is collected inside a plate put upside down on top of some cooked lentils. They solve this by distinguish between steam and water vapor (how fast the water vaporizes). However, another students add the resource of archived papers that are destroyed by moisture from the surrounding air.

They manage to continue with their reasoning by explaining that an archived paper is exposed to moisture on both sides while this sheet of paper would have a "drier" side and a more humid side and that there is a balance between the drying and the wetting (which could be interpreted as the equilibrium between evaporation and condensation).

They add that the paper should increase in temperature as evaporation, or the transition from liquid to gas, eventually will heat the paper. In this they skip the step of condensation but seem to understand that the evaporation requires energy which will be brought to the paper through heat transfer.

An explanation to the students skipping the step of condensation in this case could be that they apply a kinetic model and that this act as a barrier to condensation as they have done previously in B when explaining how heat is transferred to the hand from the steam (molecules initially move fast and slow down by hitting the hand, or in this case the paper). Thus, they do not realize that there is a phase transition occurring which releases the energy increasing the temperature of the paper.

- **C: Water in cup, observation -** Temperature → sprinkle water on skin → feel cold → temperature of paper will decrease → paper has lower temperature than a human body → water lower temperature than table → evaporation → increased humidity → heat required → water loses energy → temperature of water decreases → phase transitions from one source to another require energy → second law of thermodynamics → heat always goes from warm to cold

This section of part C was prompted by me asking more direct questions and instructions like “Look here with the IR cameras” and “What happens after it has evaporated?” (following a response that the water evaporates) as they already, from the previous section, had an idea about the evaporation of water from the glass. This may have led this section to have a pattern of talking with characteristics of cumulative talk because of those prompts.

They almost got lost by referring to the sensation of the experiment in B when one student reasoned that the paper would decrease in temperature as it felt colder when the water was sprinkled on his/her skin in B. Another student adds that a human body and a paper do not have the same temperature, which moves away from the line of reasoning of this potential response.

- **C: Paper on cup, observation** – red → warm → temperature → compare temperature of water from previous observation and temperature of paper → change in temperature because IR camera is moved → the table is surroundings → temperature of table → temperature of paper decreases to the temperature of the table → the table does not have anything to do with the paper → red → temperature → temperature increased first and then decreased → the water was colder than the paper

They begin by attending to the colors of the IR camera and translate “red” into “warm” to then give a temperature reading from the camera. The students seem surprised of the result even though they did predict the outcome of putting the paper on top of the cup with water already in the prediction phase of C. The quick line of translation is then turned into comparisons with the temperature of the water and, after a prompt from me asking them to look at the table with the IR camera, a realization that the table will have the temperature of the surroundings and that the paper is decreasing in temperature towards a thermal equilibrium. This realization is however disregarded as one student says that the fact that the table and the paper will reach the same temperature does not matter.

- **C: Paper on cup, explanation** – heat rises → paper act as insulation and keep heat in cup → heats the paper as it is aborbed by the paper
- **C: Move paper on cup, prediction** – heat will move with the paper → heats whatever it is above
- **C: Move paper on cup, observation** – temperature decreases → colder → another empty cup which the paper was moved to did not change in temperature → heat does not move with the paper to heat the other cup

Beginning with the reasoning that the paper would act as insulation and heat is absorbed by the paper as it rises from the water, the students move away from the earlier reasoning on evaporation. However, this could also be a part of the reasoning using the kinetic model and second law of thermodynamics that they have applied earlier on: Heat refers to the convection of the vapor inside the cup which then transfers heat not through condensation but conduction between gas and the solid paper explained through their kinetic model.

They did include that a phase which transfers energy by having fast moving molecules hitting a surface, loses kinetic energy and the molecules slow down which transitions the water into liquid, in part A. This step of the reasoning is not included here as it is only about heat transfer. The reasoning leads to the students predicting that the heat would move with the paper when the paper is moved over to an empty cup (really just to hold the paper) and there heat the other, empty, cup. They can disconfirm this hypothesis when they get their IR cameras and observe the paper being moved and instead find that the paper decreases in temperature.

- **C: Move paper on cup, explanation** – cold because water disappeared → condensation and then it got colder → there is no evaporation → condensation on the paper and when it is cooled down it transitions into liquid → the condensation stops → water drips down from the paper → evaporation when there is a cup of water → energy moved from the water to the paper and now it moves from paper to cup → walking out from shower or sauna is cold → the water evaporates → requires energy → it gets colder and heat is removed from the glass → paper is moved → water is still on the paper → evaporates → requires energy → requires heat → evaporation is heating

The students begin with a sound observation: Water is disappearing from the paper and it gets cold. However, when adding condensation to the reasoning process, which they have had difficulties with earlier in their discussion, when the second law of thermodynamics has acted as a barrier in the reasoning process, they move away from the productive reasoning path. Their reasoning here include water dripping from the paper down into the empty glass as a result of condensation "stopping" which then lowers the temperature. It seems that the teacher students got fixated by the empty glass which was just used to hold the paper and it thus acted as some distractor or potentially a barrier in their reasoning. The reasoning was however steered back to the productive path when one student referred to the situations in A and B (the sauna and the shower) which lead to the explanation that water evaporates from the paper which requires energy. One student added that evaporation is like it gets hotter (the latent heat required to evaporate the water could be thought of as heat transfer to the water, it does not, however increase the temperature of the water that is transitioned as it is a phase transition). The part about condensation stopping is in this context sound as it is a necessary condition in the situation for the temperature to decrease.