*Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 2280*

# Resourceful students

## *Engaging students in active and systematic investigations in laboratories involving thermal phenomena*

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**Abstract**
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This thesis focuses on students' engagement in inquiry-based laboratory learning environments. The aim of the research is to explore what it is that makes students active and systematic in these types of lab learning environments. Two theoretical frameworks, social semiotics and the resources framework, are combined to describe how students activate and employ different types of resources (conceptual, epistemological and semiotic resources) in such learning environments. The thesis provides a model, the generalized resources triangle, which is used to synthesize ideas of the two theoretical frameworks. The concept of a barrier is introduced to emphasize resources that are in conflict with, inhibit or distract other resources that may be relevant for the learning environment. The thesis is based on five (I-V) publications (four empirical papers and one book chapter). Data for the individual empirical publications (II-V) have been gathered through video recording. The methods for analyzing the processed and raw data included multimodal conversation analysis and thematic analysis. The thesis argues that active engagement relates to how novel an encountered phenomenon is and how well students recognize the phenomenon. Several resources support students' active engagement, primarily conceptual and semiotic resources (with a basis in an exploratory frame as an epistemological resource). Additionally, some of the conceptual resources (exemplars), instantiations of an exploratory frame (e.g. exploratory talk) and the employment of tools that afford instant inquiry, such as infrared cameras, can be used as indicators of active engagement. Importantly, the thesis also argues that students' own systematic engagement relates to their epistemological resources, and the semiotic resources that mediate the epistemological resources. In particular, three epistemological resources that support students' systematic engagement are identified: An exploratory frame, metacognitive reflection and procedural self-regulation (toward an inquiry-based approach). These resources are mainly practiced and developed by students' engagement with inquiry-based activities and potentially also through education on learning and development (such as courses included in teacher education). The thesis includes a discussion about how the different types of resources can be used in addressing different types of challenges during inquiry-based labs: The activation of conceptual resources can be used as a short-term solution but a more long-term solution involves activation of epistemological resources. The thesis concludes by relating the findings of the thesis to the practice of teachers, that is, implications for teaching.

*Keywords:* Inquiry-based, inquiry, infrared cameras, laboratory education, active engagement, systematic engagement, thermodynamics, phase transitions, calorimetry, curiosity, conceptual change, resources framework, social semiotics, physics education research, metacognition, laboratory skills, exemplars, instant inquiry

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*To Caspian, Nemo, Tova and LärNat*

# List of peer-reviewed publications

This compilation thesis is based on the following papers (and book chapter), that are referred to in the text by their Roman numerals. Although not all are published, they will be referred to as "publications" as not all are papers.

In this thesis, I will refer to each publication as X with X being replaced by the Roman numerals shown below. As the reader will notice, they are not in chronological order but in an order which matches how they fit together in a broader narrative for the purpose of this thesis.

Note that I-IV are peer reviewed and published and V is a manuscript.

I. Samuelsson, R. (2022). Research on educational use of thermal cameras in science: A review, In J. Haglund, F. Jeppsson & K. J. Schönborn (Eds.), *Thermal Cameras in Science Education* (pp. 47-61). Springer.

   **Author's contribution:** The chapter was based on my literature review on the topic from my licentiate thesis. I did all the work for the chapter on my own.

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II. 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.

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   **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).

III. Samuelsson, C. R., Ho, F., Elmgren, M., Haglund, J. (2023). Looking for solutions: students' use of infrared cameras in calorimetry labs, *Chemistry Education Research and Practice*, 24(1), 299-311.

**Author's contribution:** I proposed the idea of the study, carried out data collection, transcribed and analyzed the data (data sessions and discussions with co-authors inbetween iterations of transcription and analysis), wrote the initial draft for the paper and the final version (the draft was sent between all authors inbetween these two stages and all authors suggested edits and additions of sections of text).

IV. Samuelsson, C. R., Elmgren, M, Xie, C., Haglund, J. (2019). Going through a phase: Infrared cameras 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).

V. Samuelsson, C. R., Gregorcic, B., Elmgren, M., Haglund, J. (manuscript). Productive resources in students' experimental investigation of phase transition: Inquiry with a grain of salt

**Author's contribution:** I proposed the original idea of the study (modification were later made after discussions among all authors), co-designed the activity, collected the data, transcribed and analyzed the data (all analyses and transcriptions were later presented and discussed in several meetings with all authors), wrote the initial and final draft (all other authors contributed inbetween these drafts).

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

# Other supporting work

**Conference presentations**

Samuelsson, R. (2023). Att dra nytta av studenters produktiva associationer. In *Forskning om högre utbildning 2023*, Stockholm, Sweden, May 11-12

Samuelsson, R. (2023). Critical thinking: Epistemological components of students' systematic investigation in inquiry-based lab activities. In *Teknisk-naturvetenskapliga fakultetens Universitetspedagogiska Konferens, TUK 2023*, Uppsala, Sweden, March 15

Samuelsson, C. R. & Haglund, J. (2022). Productive resources in science education: The case of adding salt to ice. In *Forskning i Naturvetenskapernas Didaktik*, Sundsvall, Sweden, November 8-10

Samuelsson, R., Gregorcic, B., Elmgren, M. & Haglund, J. (2022). Productive epistemic games in an Investigative Science Learning Environment, In *GIREP 2022*, Ljubljana, Slovenia, July 4-8

Samuelsson, C. (2021). Resources and semiotic resources. In *7th International Designs for Learning Conference* (virtual), May 25-26

Henriksson, J. & Samuelsson, R. (2021). Transitioning into a discipline - exemplars as cognitive resources in learning physics, *Nordic Physics Days 2021* (virtual), Uppsala, Sweden, August 4-6

Samuelsson, C. (2021). A proposal for a theoretical construct to acknowledge restricting or distracting resources. In *Nordic Physics Days* 2021 (virtual), Uppsala, Sweden, August 4-6

Samuelsson, R. (2021). Resources and barriers in reasoning. In *ESERA 2021* (virtual), August 30-September 3

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

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, July 10-15

Samuelsson, R., Elmgren, M., Haglund, J. (2018). Going through a phase. In *The Gordon Research Seminar on Physics Research and Education,* Bryant University, Smithfield, RI, US, June 9-10

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

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, August 21-25

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, December 7-9

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

**Papers**

Nygren, T., Haglund, J., Samuelsson, R., af Geijerstam, Å., Prytz, J. (2019). Critical thinking in national tests across four subjects in Swedish compulsory school, *Education Inquiry*, 10(1), 56-75

**Licentiate thesis**

Samuelsson, R. (2020). *Reasoning with thermal cameras: Framing and meaning-making in naturalistic settings in higher education*. [Licentiate thesis, Uppsala University].

# Contents

# Preface

## About the author of this thesis

I have been a part of the academic world for 15 years. My journey started at the Ångström laboratory in 2008 at the tekniskt basår (preparatory year in natural science) where I, among others, was taught by Johan Larsson in physics, Susanne Mirbt in mathematics, Håkan Rensmo in chemistry and Jannika Andersson Chronholm in biology.

I have always had a great interest in both natural and political science and my path at the university reflects 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 involved (as a volunteer) at one of Uppsala's student nations (student association), 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). Additionally, I occasionally worked as a teacher in mathematics and chemistry during my studies.

I have continued to teach during my Ph.D. studies. This includes teaching subjects and courses related to my research such as physics for chemists, cognitive science for teachers, chemistry education research for chemistry teacher students, supervision of teacher student projects, assessment of physics and math teachers' practice, mathematics for the introductory year in science (naturvetenskapligt basår) and scientific methods for teacher students. I believe that teaching is an important aspect of being a scholar, especially one involved in education research.

I have also been involved in some outreach activities by arranging experiments with IR cameras for the public and employees at the faculty of science and technology.

All of these commitments have shaped who I am today but they also mirror my interests and current 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 my papers. However, the work of my papers was a collaborative effort of all the involved authors. My contributions to each paper are expressed in the List of peer-reviewed publications. The thesis is a result of my own individual effort though (with highly appreciated feedback from my colleagues). This thesis builds and expands on the licentiate thesis that I defended in 2020 (R. Samuelsson, 2020). I will at times refer the reader to the licentiate thesis.

Publication I is a review of previous research involving infrared cameras and education. It builds on the review that I wrote for my licentiatie thesis and is therefore presented in 3. Previous research. Publication II-V include the empirical studies that this thesis builds on.

Many of the figures come from either my publications, the supporting work or the licentiate thesis.

## Relating the licentiate thesis to the doctoral thesis

My licentiate thesis Reasoning with thermal cameras (R. Samuelsson, 2020), which built on II and IV, had a focus on the tools (IR cameras in particular) that can be used to investigate thermal phenomena in lab education in addition to students' conceptual resources and talk employed when engaging with lab activities based on the probing method Prediction-Observation-Explanation (White & Gunstone, 1992).

This doctoral dissertation expands on the ideas from the licentiate thesis by also focusing on the type of learning environment (inquiry) and what types of epistemological resources that are important when dealing with inquiry-based lab activities of varying degrees of openness. Additionally, this thesis will also discuss how conceptual resources, like the ones discussed in the licentiate thesis, relate to students' engagement in inquiry-based lab activities.

Parts of the licentiate thesis are reused (most often reworked) in this doctoral thesis. This includes parts of chapter 1 (reworked for the thesis), parts of chapter 2 (that have been reworked to fit the purpose of this thesis), 3.1, parts of 3.3 (in 3.3.1, 3.3.2 and 3.3.4), parts of 3.4, parts of 5.1-5.6 and parts of the summaries of the publications (II and IV) included in the licentiate thesis (6.1 and 6.3).

There are, however, larger sections of the licentiate that are not repeated in this thesis, for example the full literature review with tables of the reviewed publications, an overview of the history of physics education research, and an longer overview of thermodynamics education research and visualization in education. I refer the reader to the licentiate thesis to read these. Additionally, I have shortened the summaries of the publications as much of it is available either in the publications or in the licentiate thesis.

## 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 might have a significant value to peers in education research, but that might not be as easy to just apply in a classroom setting. I recommend reading chapter 8 for some recommendations on how to apply my results to a teaching context.

# Glossary

What follows is a list of central concepts and terms that I use in this thesis. Each concept or term is followed by a description of how I have decided to use them in my work (i.e. a definition), sometimes with references to previous work.

*Active engagement*[1] – To be actively engaged is mainly to be mentally active. The active engagement can, however, take on many forms of expression such as speech and gestures. To be actively engaged within a learning environment means to be mentally active in relation to the environment, i.e. to think about and relate experiences within the learning environment to one's previous experience. To make meaning about the experiences in the learning environment is thus to be actively engaged in the learning environment. In this thesis it is generally assumed that active engagement refers to the instrinsic (on the students' own initiative) active engagement.

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

*Barrier* – I draw on the idea of Loverude, Kautz and Heron (2002) to acknowledge the cognitive resources that might lead to a, for the activity, challenging situation. This can happen from cognitive resources that distracts, inhibits or are in conflict with other cognitive resources.

*(Conceptual) framing/frame* – A coherent activation of resources that are used to interpret a situation in a way that answers the question "What is this about?" (Hammer et al., 2004; Redish, 2014).

*Conceptual resource* – The building blocks of what we think.

[1] I follow Dehaene (2021) in the use of the term active engagement instead of active learning. Active engagement can be active learning but I have chosen engagement rather than learning as learning implies something about the assessment of the students in relation to some course goals or assessment matrix.

*Disciplinary affordance* – The concept can be defined as "the agreed meaning making functions that a semiotic resource fulfils for a particular disciplinary community" (Airey, 2015, p. 18).

*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* – In my thesis, epistemology involves ones beliefs about how one comes to gather and share knowledge.

*[Epistemological] framing/frame* – The interpretation of what to do in a situation in order to gain or share knowledge about the reality.

*Epistemological resources* – The resources that control how we think. Epistemological resources are related to metacognitive skills as they both involve thinking about the nature of something. Epistemological resources have also been described as being closely related to one's epistemological frame in previous research (e.g. Richards, Jones, & Etkina, 2020).

*Everyday knowledge* – The term refers to knowledge from informal contexts (outside formal education).

*Exemplar* – Illustrative event, situation or instance. The individual members of a [mental] category (Nosofsky & Zaki, 2002). Prototypes and exemplars are assumed to be the same construct in this thesis (and referred to as exemplars).

*Inquiry-based learning environment* – Learning activities that are designed with students' inquiry in mind (for example Investigative Science Learning Environment activities). These learning environments involve students investigating phenomena more freely than a traditional, step-by-step, lab. In other words, there is some degree of openness to inquiry-based learning environments.

*Instantiation* – A representative concretization of an abstraction.[2] For example, the instantiation of an epistemological frame could be the actions, or behavior, that displays the frame to the environment.

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[2] It is possible to relate the relation between concretization and abstraction to the distinction between token and type offered by Peirce (1906). Peirce describes tokens as single events or objects that, in use, are referred to as instances of the type. When a type is used (i.e. an instance) it "has to be embodied in a Token which shall be a sign of the Type, and thereby of the object

*Instant inquiry* – When "acting immediately upon "what-if" questions driven by [..] genuine curiosity" (Haglund et al., 2015).

*Instructional approach* – The philosophy and method of the type of instruction. Examples of instructional approaches are Investigative Science Learning Environment and Prediction-Observation-Explaination.

*Instructor* – Refers to the lab assistant in undergraduate courses, corresponding to "instruktör" in Swedish.

*Learning environment* – The setting and the instructions within which an activity is carried out. In other words, this involves such aspects as the room itself and the equipment but also the instructional approach. A learning environment can involve several activities or a teaching sequence.

*Meaning making* – Meaning making involves the process of making sense or understanding an encountered experience by relating what is encountered with one's previous experience (formal or informal) (e.g. Zittoun & Bringmann, 2012). Meaning making can involve many different types of semiotic systems and is thus multimodal (e.g. Danielsson, 2016).

*Metacognitive reflection* – Involves the reflection on one's own knowledge, e.g. the reflection on what type of knowledge one is engaged with, how different types of knowledge are related to different roles (e.g. teacher versus student) or limitations of one's knowledge and how one's knowledge is organized).

*Naturalistic settings* – The setting of the practice of the studied participants 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 mechanics).

*(Degree of) openness* – The degree of openness gives an indication of the freedom in making decisions in a learning environment. A learning environment of a high degree of openness is close to an authentic discovery or what we do as researchers. A learning environment of low degree of openness is close to direct instruction.

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

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the Type signifies" (Peirce, 1906, p. 506). However, my use of instantiation also include indefinite characters such as types of talk. Peirce calls types of signs tones to disinguish them fron definite characters (i.e. tokens).

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

*Procedural self-regulation* – A term that draw on an idea of Zimmerman (1986) to describe how students, on their own initiative, regulate their practice. In particular, it has been (in V) used to describe how students regulate their practice toward an ISLE-based procedure. I will often just use "procedural self-regulation" in this thesis but it is assumed that this involves a procedural self-regulation toward ISLE or some other inquiry-based approach with a guiding structure.

*Productive* – A resource or behavior is productive when it leads to a progression in students' thinking. The definition is similar to the definition of situated productiveness (Goodhew et al., 2018; Harrer, 2013). This could for example be resources that promote active engagement or resources that promote systematicity. When I use the term in relation to previous research, it is used as it is defined by that research.

*Prototype* – An average representation of multiple members of a category (Gärdenfors, 2004; Nosofsky & Zaki, 2002).

*Railroaded* – A railroaded learning environment or activity is highly guided. The term is commonly used in gaming (in particular tabletop roleplaying games) when referring to different constraints added by a game master that make the players progress in a certain direction. For my use of the term, the game master can here be replaced by the designer of the learning environment and the players by the students. The constraints can for example be specific prompts, which can be compared to cookbook lab instructions.

*(Cognitive) resource* – Tools and ways of knowing (Redish, 2014), in a cognitive sense, or knowledge elements (Redish, 2004). There are both conceptual (the "content" or "building blocks" of what we think) and epistemological resources (the resources that control how we think). I use the term (cognitive) resource as an umbrella term for the many types of cognitive "units" of different grain sizes that represent knowledge in different types of cognitive models, e.g. ontological categories (Chi & Slotta, 1993), phenomenological primitives (diSessa, 1993), heuristics (Tversky & Kahneman, 1973), and exemplars and prototypes (Nosofsky, 2010; Nosofsky & Zaki, 2002; Rosch, 1973). As such, my use of the concept more closely resembles what Redish (2004) refers to as patterns of association. Frames are also included in my definition of cognitive resources.

*Scaffolding* – Support or guidance provided during learning. This can for example be done through a teacher asking guiding questions, by contextualizing a learning situation in a way that makes the content more accessible for the students or through the instructive structure.

*Semiotic system* – A category or mode of communication, e.g. colors, numbers or gestures.

*Semiotic resource*[3] – A specific member of a semiotic system, e.g. red (system: color), 56 (system: number) or the right hand rule gesture (system: gesture).

*Systematic engagement* – Systematic engagement involves a structured and coherent approach to the learning environment. In addition to the reasoning being coherent and easy to understand, each new phase of the students' activity builds on a previous phase (e.g. base a hypothesis on a previous observation, a lab design around testing a hypothesis), and there is a direction in their activity. Students can be systematic without being actively engaged (for example, in a railroaded activity with less open instructions) and coherent without being systematic (for example, individual lines of reasoning being coherent, but without connecting to previous activities).

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

*Tool* – Tools are one or several (a collection of) semiotic resources, for example a thermometer.

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[3] When referring to semiotic resources communicating or carrying some meaning from one person to be interpreted by other people I will use mediate (semiotic resources that mediate…) and for semiotic resources that gather and display information from the surroundings, I will use convey (semiotic resources that convey…). I use information for potential knowledge that does not have a thought process behind it and meaning for knowledge that has a thought process behind it.

# Abbreviations

| | |
|---|---|
| *CA* | Conversation analysis |
| *CER* | Chemistry Education Research |
| GMCC | General Model of Conceptual Change |
| *IBLE* | Inquiry-Based Learning Environment |
| *IPLS* | Introduction to Physics for Life Science |
| *IR* | Infrared |
| *ISLE* | Investigative Science Learning Environment |
| *LLM* | Large Language Model |
| *MBL* | Microcomputer-based labs |
| *MCA* | Multimodal conversation analysis |
| *NGSS* | Next Generation Science Standards |
| *PER* | Physics Education Research |
| *POE* | Predict-Observe-Explain |

# 1. Introduction

## 1.1 My research journey and the choice of topics

My interest in science education research and subsequently physics education research began with my interest for the research on misconceptions in science which was introduced to me in a book by Eilks and Hofstein (2013). I later went on to study how the atomic models were presented in different types of chemistry high school textbooks by applying the research of Gilbert and Justi (2000, 2003) on hybrid models and the use of historical models to teach science. It was during my work on this project that I became interested in research on metaphors and analogies in science, which lead me to read a book on the topic (Jeppsson & Haglund, 2013). I was already interested in linguistics, in particular the work of classic scholars like Wittgenstein and de Saussure so the research by scholars such as Peirce, Lakoff and Johnson fitted nicely with this interest.

My Ph.D. studies started off with a broad focus on thermodynamics and educational use of IR cameras. I have always had an interest in thermodynamics as it ties many of the natural science disciplines together (although there are some differences in terminology and what types of problems that are exemplaric for each discipline (Christiansen & Rump, 2008)). Studies on students' difficulties with understanding the energy concept in different contexts (e.g. Dreyfus, Gouvea, et al., 2014; Dreyfus, Sawtelle, Turpen, Gouvea, & Redish, 2014) have been important in relating disciplines such as physics and chemistry to each other for educational purposes and the research on the difficulties with understanding the concept of heat (e.g. Erickson, 1979; Piaget & Garcia, 1977) has not only been important in understanding how we should teach thermodynamics in both physics and chemistry but also in the development of conceptual change as an approach to study teaching and learning (Posner et al., 1982).

There are many interesting topics in thermodynamics but I chose to focus on physical changes, in particular concerning heat transfer and temperature change in topics such as phase transitions and calorimetry as they have proven to be topics that have not been investigated much in previous research. Significantly, these were topics in which IR cameras can be used in a purposeful way to visualize the heat transfer. Additionally, I found the idea of leveraging calorimetry in physics education to teach about heat transfer and temperature as McDermott (1996) did in her Physics by Inquiry interesting and novel (even though the book was published almost three decades ago).

Another significant feature with phase transition and calorimetry as topics is that many phenomena in these topics are approachable from an everyday perspective (such as the condensation of water on the body when sitting in a sauna, water in a glass evaporating overnight and temperature changes when adding table salt to solid or liquid water).

When it comes to the theory and research, I have always been fascinated by research on cognition and communication. In particular, I have had a great interest in research on heuristics (e.g. Kahneman, Slovic, Tversky, & Kahneman, 1974; Talanquer, 2014), attention (e.g. Simons & Chabris, 1999; Wood & Simons, 2017) and prototypes/exemplars/collective memories (e.g. Gärdenfors, 2004; Manier & Hirst, 2008; Nosofsky & Zaki, 2002; Rosch, 1973), and research on types of talk (Lemke, 1990; Mercer, 1995), the meaning of symbols (e.g. de Saussure, 2011; Kress & van Leeuwen, 2002; Norman, 2013; Peirce, 1985), family resemblance (Rosch & Mervis, 1975; Wittgenstein, 1968) and metaphors/analogies (Grady, 1997; Lakoff, 1987; Lakoff & Johnson, 1980). The choice of theory for my thesis hopefully reflects these interests: My research is based on ideas from social constructivism and cognitivism (a combination of cognitive science and constructivism) through the frameworks of social semiotics (e.g. Airey & Linder, 2017; Jewitt, Bezemer, & O'Halloran, 2016) and the resources framework (Hammer, 2000; Redish, 2004).

Cognitive perspectives and sociocultural perspectives have different traditions and epistemologies (but they do also share many ideas (Piaget, 2000)). Scholars employing frameworks related to the sociocultural perspective, such as social semiotics, sometimes tend to have a skeptical view towards the cognitive perspective as they argue that the cognitive perspective ignores social and biological aspects and isolates the cognition from any social process (e.g. Ivarsson, Schoultz, & Säljö, 2002; Lemke, 1990) or that a cognitive perspective can not account for why an individual makes different meanings for different situations (e.g. Lidar, Almqvist, & Östman, 2010). However, it is difficult to argue that there is any homogenous perspective that could be referred to as "cognitive" and there are researchers that employ an approach, that could be considered involving cognition, that do not exclude social or biological aspects from their research, in particular branches like embodied and situated cognition (e.g. Lave, 1988; Shapiro, 2019). In fact, even Piaget (2000) admitted to agreeing with Vygotsky on the function of language and based much of his research on how biology relates to cognition (although he did also admit to disagreeing with Vygotsky on many points about socialization). Others have discussed how it could be possible to bridge the gap between the perspectives (e.g. Halldén, Haglund, & Strömdahl, 2007; Mason, 2007) but attempts of bridging the perspectives that do not regard the individual and the environment as interdependent have been met with skepticism and the activity has been suggested as a more appropriate unit of analysis when analyzing the individuals, social partners, materials and other social aspects (Rogoff, 1995). It is not always clear what the conflicting perspectives are as it sometimes is a conflict between constructivism and cognitive science (Kirschner et al., 2006; Mayer, 2004), the sociocultural perspective and cognitive perspective (Ivarsson et al., 2002) (which can include constructivism) and other times the sociocultural perspective and mentalism (Lemke, 1990). It has also been suggested that we should explore the differences rather than creating a synthesis as they "have a long history in western philosophy, and the difference between them is of a paradigmatic nature that cannot be easily resolved by appealing to empirical data" (Ivarsson et al., 2002, p. 78).

Researchers in physics education research have been more eclectic when developing the theoretical frameworks that are used within the discipline. When outlining the resources framework, Redish (2004) draws on ideas of both cognitive perspectives and sociocultural perspectives through the grain-size staircase (Redish, 2014) (Figure 2) in order to find a more pragmatic common ground between the perspectives. I follow this more eclectic approach.

The cornerstone of my research is students' activity. Students' activity in the laboratory is of particular interest for several reasons and I will provide the reader with some of the reasons here. Firstly, lab education is fundamental for physics, but the purpose of labs has been a highly discussed topic (Bernhard, 2010; Hofstein & Lunetta, 1982; Holmes & Wieman, 2018). Secondly, labs are highly related to learning perspectives such as pragmatism and constructivism (learning by doing and learning by building on one's previous experience). Finally, *active* and *systematic engagement*, two activities of interest for this thesis, are also critical activities in more open labs and inquiry-based lab learning environments are therefore of interest for the work in this thesis.

I have mainly turned to social semiotics to study environmental or social aspects of my data and the resources framework in order to study cognitive aspects of students' reasoning and practice in terms of their epistemologies. I have found it both useful and convenient to combine the two frameworks as the resources framework allows for sociocultural ideas as a part of the framework but do lack a focus on the tools students use to mediate meaning with. I have also included other theoretical constructs that fit with the epistemologies of social constructivism and cognitivism, such as the concept of *affordance* (Gibson, 1979; Norman, 2013) to study how tools and representations are used and interacted with, Mercer's (1995) *typology of talk* to study students' communication, and *exemplar* and *prototype* theory (e.g. Smith, 2014) to study the content of students' reasoning, just to name a few of the other constructs that have been used in my research.

I have used several methods in collecting, processing and analyzing the data in my research. These includes, but are not necessarily limited to, *Predict-*

*Observe-Explain* (White & Gunstone, 1992) and *Investigative Science Learning Environment* (Etkina et al., 2021) to probe students, video and audio recording to collect the data, multimodal transcription to process the data and *multimodal conversation analysis* (e.g. Jewitt et al., 2016) and *thematic analysis* (Braun & Clarke, 2012) to analyze the data.

## 1.2 Purpose and structure of the thesis

The purpose of the research is to identify what resources (conceptual, epistemological and semiotic resources) support two types of student activity in inquiry-based labs, both active and systematic engagement, and ways that students can address challenges that they encounter during their activity.

The thesis is structured in the following way:

- Chapter 1 is an introduction to the thesis which involves placing myself as a researcher in the field and the chosen physics topic (thermodynamics).
- Chapter 2 provides an overview of the theoretical framework of the thesis.
- Chapter 3 describes some of the previous research that relates to my research.
- Chapter 4 outlines the research questions of this thesis.
- Chapter 5 provides an overview of the general philosophy that has guided my choice of methods, the methods, and the trustworthiness and ethics of my research.
- Chapter 6 provides an overview of the individual publications and the additional analysis from the licentiate thesis on the findings from II and IV.
- Chapter 7 is central to thesis as this is where I present the emerging themes and patterns from across the individual studies.
- Chapter 8 provides specific answers to the research questions, contributions to the field of physics education research, and a discussion on the implications of my research for teaching.

# 2. Conceptual framework

I will here describe the two frameworks that are fundamental to my research. I describe this synthesis as a conceptual framework, i.e. a framework that "explains […] the main things to be studied – the key factors, constructs or variables – and the presumed relationships among them. Frameworks can be rudimentary or elaborate, theory-driven or commonsensical, descriptive or causal" (Miles et al., 2014, p. 20).

## 2.1 The learning perspectives

> If I have to reduce all educational psychology to just one principle, I would say this: the most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly
> (Ausubel, 1968, p. vi)

There are numerous ways of defining *learning*: In one of his early studies, Säljö (1979) showed that there are distinctive differences between people in terms how we think about learning, and he argues that it seems to relate to differences in experience of learning. The first view is that learning is just memorization of facts and the second view is that learning is thematic (i.e. there are different types of learning). The latter includes themes such as learning is influenced by context, learning for life versus learning in school and the difference between learning and understanding.

Each way of thinking about learning can be described through a learning perspective, which can essentially be viewed as being built on a set of axiomatic assumptions. I will here briefly present some of the perspectives that I have chosen:

*Constructivism* is a perspective of learning that is based on the assumption that learners build on their previous experience when learning. Ausubel As this perspective can encompass many different views, Knight (2004, p. 42) in the context of university physics education, coined the term *scientific constructivism* for 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 experience.

This view does not exclude the epistemology of *cognitive science,* or *cognitivism,* in which commonly models how we organize or represent our knowledge in cognitive science through *nodes* and *connections*, more commonly known as *connectionism* (Gärdenfors, 2004). Also, cognitive science acknowledges the role of the learners’ experience, but in terms of 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, such as what happens *in their minds*, for example from whatever the study objects are talking about or how they behave. Additionally, I subscribe to the idea that our cognition is embodied, i.e. a cognitive process does not have to end in the mind (Clark & Chalmers, 1998), and that it is “stretched across mind, body, activity and setting” (Lave, 1988, p. 18). Here, I argue that this is similar to what is referred to (Kersting et al., 2023) as the cognitivist perspective on the role of the body for learning in science education.

A third important learning perspective is the *sociocultural perspective,* which revolves around mediation through semiotic systems such as mathematics, gestures in learning. Researchers committing to this perspective can sometimes have a skeptical view towards cognitive perspectives (see Lemke, 1990) and there is thus some tension between cognitive perspectives (that focus on mental functions and the individual) and models or perspectives that builds on the sociocultural perspective. 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 had not 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[4] do not have someone to talk to (*egocentric speech*), is used to coordinate the actions. Hindering such speech can even lead to hindering the accomplishment of the task. When the learner does not find a solution on her own, she can turn to a peer or a teacher and communicate through *socialized speech,* which is then internalized. That is, the spoken language that goes on between learners tells us something about the learning on both a social and cognitive level. Although spoken language is often the central way of communicating something, other means of communication are also included in my perspective, for example gestures and positions. This is the assumption that I bring with me from this learning perspective: the multimodal ways that students use for communication, can be used to analyze the mind in terms of learning, or rather, *meaning making,* as they *carry* or *mediate* the ideas of students. This aligns with what has been described (Kersting et al.,

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

2023) as the social-interactionist perspective on the role of the body for learning in science education.

It has been argued that learning physics essentially is about *meaning making* (Brookes & Etkina, 2015). In this thesis, I have made the choice to use *meaning making* rather than learning as there can be many problems in trying to gain knowledge about whether a student has understood or learnt something: the result on a test showing that someone has understood something can only last for a short period of time (e.g. Dunbar, Fugelsang, & Stein, 2007), and students' self-reported perception of learning can be misleading when assessing whether they have learnt something (Deslauriers et al., 2019; Ware & Williams, 1975).

There is also something to be said about my perspective on the learner and the learners, i.e. the individual versus the group. All of my studies involve groups of students (mostly pairs) and they are treated as units when it comes to the analysis of their overall productivity or progress in some lab activity. Among the individuals of a group, it is possible to identify particular ideas that initially "belong" to one individual of the group, for example a student remembering a specific situation that relates to whatever they are working with but as soon as that idea is shared among the others in the group it will no longer belong to the individual but will allow the other students to build on the idea (or reject it if they do not have any way of relating to it). This is perhaps more related to a social-interactionist perspective, but I would argue that I also do pay attention to the pre-state of knowledge when I consider the individual's idea as a starting point for some process (whether it is social, cognitive or both), which would not be as interesting for a social-interactionist (Kersting et al., 2023). The result and progress of an activity is always considered to belong to the group or pair in my studies.

Whenever I refer to students' *learning* in the thesis[5], I refer to students' *meaning making* (as mentioned earlier). Meaning making involves interpretation of situations in the light of ones experience, i.e. how people make sense of a situation by "drawing on their history of similar situations and on available cultural resources." (Zittoun & Bringmann, 2012, p. 1809). In this sense, learning involves establishing a meaningful relation to whatever one is investigating so that it makes sense (Zittoun & Bringmann, 2012). Brookes and Etkina (2015) can be seen as following a social semiotic approach by defining learning as meaning making and conclude that it is important to teach the meaning of concepts before the technical terms as concepts are fundamentally about the semiotic resources that we use to make sense of observed phenomena. Lundqvist (2009) relates meaning making to both learning and socialization and points out that it is common that learning is related to concepts and

[5] There are times in this thesis where I do use the term *learning*. This is often because it has been used in this way in some of the litterature I refer to. In so doing, I am still referring to meaning making.

factual knowledge while socialization is related to norms and values. I agree that including socialization in meaning making (as meaning making within a discipline like physics) also involves developing fruitful habits (Etkina et al., 2017).

My theoretical framework is a synthesis of mainly two larger frameworks: The resources framework and social semiotics. There are three concepts that are of a particular importance for my research: semiotic resource (from social semiotics, and conceptual and epistemological resource (from the resources framework). Students' activity can be described with a basis in these three concepts through what I have modeled as the generalized resources triangle (see Figure 1). These concepts will be elaborated on in the upcoming sections.

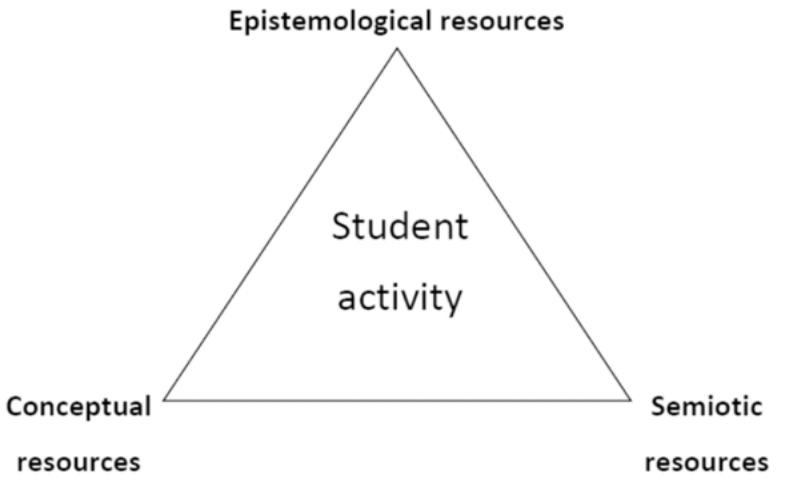


*Figure 1. The generalized resources triangle. A student activity can be described with three central concepts: semiotic resource, epistemological resource and conceptual resource.*

## 2.2 The resources framework

I now provide a brief overview of the historical path of the first framework that I use in my research (the resources framework). A central piece of this path is the conceptual change perspective that has influenced education research across all the science disciplines for decades. Although they are sometimes referred to as "theories", I will, in line with Potvin et al. (2020), refer to the different types of conceptual change as *models*. This is because I believe it puts the emphasis on their usefulness for testing ideas, i.e. each model links some insights from data (such as students' ways of answering a question) to a learning theory (e.g. cognitivism or pragmatism) that postulates the assumptions or axioms for the area that is investigated (e.g. how students reason or why students choose to use a particular equipment for lab work). So just like how the quantum mechanical model of the atom links data with quantum mechanics as a theory in physics by emphasizing the probability-based nature of electrons' locations, a conceptual change model links the theory of constructivism with data by emphasizing how previous knowledge affects development of new knowledge.[6]

Describing conceptual change in terms of models also aligns well with the ongoing European discourse in science education where it is common to see emphasis on the production of didactical models as a goal in education research (Hamza & Lundqvist, 2023; Wickman et al., 2018).

There are many models of conceptual change (e.g. see Amin et al., 2023; Potvin et al., 2020). I will mainly focus on how the resources framework developed as a response to conceptual change theory along the following path: Piaget (1954) → Posner et al. (1982) → diSessa (1993) → Hammer (2000) → Redish (2004) (including some additional work that was important for the path).

### 2.2.1 Conceptual change

The idea about students' initial conceptualization of how the world works and how to "change" these gained educational attention long before Piaget (1954) began his studies on childrens' conceptions and conceptual change. However, Piaget's research brought empirical evidence of children's thinking and conceptualization (Linn, 2008).

The paradigm of conceptual change is a very broad paradigm with several different models for conceptual change (Potvin et al., 2020). I will here mainly focus on the ideas that led to the development of one of the more popular models of conceptual change (Potvin et al., 2020), the general model of conceptual change (Posner et al., 1982), and the reaction against ideas in the model that led to the development of one of the frameworks I use in my research, the resources framework.

Research in education has over time used different words to describe the ideas that students start out from. They are often referred to as *misconceptions, preconceptions* or *alternative conceptions* (e.g. see Clement, 1987; Hewson & Hewson, 1984; Johnstone, MacDonald, & Webb, 1977; Posner et al., 1982; Sokoloff, Laws, & Thornton, 2007). However, researchers have argued the need to distinguish between these constructs (Clement et al., 1989). This is because, for instance a preconception can be "incorrect" in a disciplinary use

[6] For further comparisons between theory, model and experiment in physics and education research, see Tiberghien (1994).

yet quite adequate for everyday use (heat being a relevant example). In addition, subsequent research has shown how the productiveness of the preconceptions depends on the context in which they are used (Dreyfus, Sawtelle, et al., 2014; Wittmann et al., 2019) and that conceptualization is *dispersed* across contexts (e.g. light as a wave or a particle) (Linder, 1993; Linder & Marshall, 2003).

Early research (e.g. Erickson, 1979, 1985; Mak & Young, 1987; Warren, 1972) in physics and science education research, on students' understanding of concepts such as heat and temperature, focused on revealing students' conceptions. For example, the erroneous (i.e. non disciplinary) idea that energy transferred to a body of matter through radiation "becomes" heat when absorbed by said body (Warren, 1972). Up until the work of notable constructivist researchers of the post-Piaget era, for example, Gaalen Erickson[7] and Rosalind Driver (e.g. 1983), and Andrea diSessa (1993), this strand of research tended to regard students' ideas as coherent and stable. This coherent and stable dynamic meant that research still lacked a model that could describe what so-called misconceptions are and how to deal with them. Consequently, several models of conceptual change have been developed and continue to be developed (Potvin et al., 2020). Probably the most infuential of these (Potvin et al., 2020) is the *General Model of Conceptual Change*, or GMCC (Posner et al., 1982). Posner et al. (1982) based their model on the ideas of Piaget (1952), Toulmin (1972), Lakatos (1970) and Kuhn (2012) in order to develop "a reasonable view of *how* a student's current ideas interact with new, incompatible ideas" (1982, p. 211).

The general model of conceptual change builds on the idea that students deal with new knowledge either through assimilation or accommodation, two constructs developed by Piaget (1952). If the student's current conceptual ecology (a term from Toulmin (1972) to describe the individual's current concepts) is in line with, or can deal with the new knowledge, they assimilate the knowledge. However, if the students cannot use their current concepts to deal with the knowledge or if their current knowledge contradicts the new knowledge, they have to accommodate for the new knowledge. In this case, learning requires a radical change in the student's conceptual system, which includes the replacement of old ideas with new ideas. In developing their model, Posner et al. (1982) compared the conceptual change of the individual with how research programs and paradigms change (Kuhn, 2012; Lakatos, 1970) and thus formed an analogy between the learning of the individual and the macroscopic changes of cultures. Thus, they argued that the individual would reject ideas for new ones given enough evidence against the idea (just

[7] A significant seminal work set in a constructivist framework was the doctoral dissertation of Erickson (1975, 1979). Erickson's (1975, 1979) research on children's conception of heat and temperature was also fundamental for the development of the *General Model of Conceptual Change* (GMCC) (Posner et al., 1982).

like how a paradigm would change given enough anomalies). The authors described the moment in which an individual is prepared for conceptual change in terms of accommodation as a cognitive conflict (a crisis in a Kuhnian perspective).

The conceptual change models led to a sort of revolution in science education and was and continues to be viewed as a valuable educational perspective. Within physics education research, tests for eliciting students' preconceptions and common-sense distractors, and identifying misconceptions, were developed in connection with the emergence and popularity of the paradigm in the field of research. These include tests of students' conceptions in Newtonian mechanics such as the Force Concept Inventory (Hestenes et al., 1992) and the test of initial knowledge states of mechanics (Halloun & Hestenes, 1985). Other concept inventories have later also been developed, and are still developed, for other topics in physics (Docktor & Mestre, 2014). Additionally, methods such as Prediction-Observation-Explanation or POE (White & Gunstone, 1992), Elicit-Confront-Resolve (e.g. Mcdermott, 2001) and Elby pairs (Elby, 2001) for eliciting students' preconceptions were developed partly in order to deal with students' difficulties with making sense as intended. Mazur (1997) developed Peer Instruction as an instructional approach after having realized that what he previously had thought of as successful teaching "was a complete illusion, a house of cards" (Lambert, 2012), after having tested his students with the Force Concept Inventory, which showed that a majority of the students "were modern Aristotelians" (Lambert, 2012).

During the same time and some years after the GMCC had been proposed there were many researchers in education that entertained the notion that learning is contextual or situated. These were not direct responses to conceptual change as a model, but rather a response to the idea that learning can be described in general terms out of context. Some of the more famous results from these discussions include Lave's (1988) Cognition in Practice, which questions the research on learning transfer across contexts and how context as a term has been ambigiously used in previous research: "ambiguous usages [of context] makes it possible to equate the circumstances in which transfer is studied with the much broader circumstances in which it is supposed to infuse everyday activity with academic expertise" (Lave, 1988, p. 40). In the book, Lave argues that situations affect how we use the same type of knowledge. For example, arithmetic skills are shown to be used differently in the grocery store and in formal problems that present the same problems in classrooms that arise in the grocery store, i.e. the situation and its practice affect how we use our knowledge (or our activity in Lave's terms).

There are other cracks in the paradigm. It has been argued that, at least in physics education research, there are "two apparently contradictory theoretical perspectives – students' conceptions as coherent or students' conceptions as fragmented" (Brown & Hammer, 2013, p. 122).

### 2.2.2 The response to the traditional conceptual change

After the proposal of the GMCC, and other models of conceptual change, during the 1980s, some researchers (e.g. Hammer, 1996; Linder, 1993) began questioning the fundamental idea of students' conceptions as stable across contexts. Linder (1993) proposed a way to describe conceptual change from the perspective of the relation between a person and a context. He argued that teachers should focus on teaching students how to recognize the appropriateness of different models in particular contexts. Similarly, diSessa (1993) and Hammer (2000) proposed context-dependent models that assume that students' conceptions are fragmented, in addition to ways of leveraging students' productive preconceptions (e.g. Clement, 1993; Hammer et al., 2004). One such model that involves context-dependent conceptual change (in contrast to GMCC) is the knowledge-in-pieces model (diSessa, 1993).

Learning perspectives, or learning theories, that assume that it is possible and worthwhile to study how our mind works when we learn, 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, e.g. they are explained by "That is just how it is". He calls these constructs *phenomenological primitives* (*p-prims*). We form such primitives from experiences early in life. 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 can be self-explanatory and have the function of *axioms of our intuition*. The aim of education is to help learners 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 (diSessa, 2014). That is, to learn in what contexts to apply a certain composition of resources for it to be *productive*, e.g. useful in coming to a, for the teaching situation, correct answer. A context in this case would "heuristically refer to an […] 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" (diSessa, 1993, p. 180), i.e. cues from the environment that prepares for a certain type of thinking. For example (Redish, 2004), a student in physics can 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 can 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).

Another response to conceptual change that focus on students' misconceptions is the *resources framework* (Hammer, 2000; Redish, 2004). Sabo, Goodhew and Robertson (2016) compare the stances on intuitive knowledge, assumptions and agendas of research on misconceptions and the resources framework (see Table 1).

*Table 1. A comparison between research focusing on students' misconceptions and students' resources. Based on a summary of Sabo, Goodhew, and Robertson (2016).*

| | *Misconceptions* | *Resources* |
|---|---|---|
| *Stance on students' intuition* | Inconsistent with scientific view. Barrier to development of correct understanding | At times consistent with the scientific view (depends on context) |
| *Assumptions* | Student knowledge is rigid | Student knowledge is dynamic |
| *Research agenda* | Search for incorrect patterns in students' reasoning | Search for productive ideas in students' reasoning |
| *Instructional agenda* | Elicit, confront and resolve students' misconceptions | Base it on and refine what is intuitive for students |

The resources framework, and research building on the framework, aligns well with the core ideas of constructivism that also influenced the early conceptual change models: For example, that each individual is unique in terms of ideas, that it is possible to model students' conceptual structures and that students' ideas will impact how they learn science (Taber, 2006). However, in contrast to the conceptual change models that concern so-called misconceptions, the resources framework mainly puts emphasis on the productive ideas rather than the problematic ideas (see Table 1).

There are some core concepts of the resources framework. The next section will elaborate on these.

### 2.2.3 Toward the resources framework

The idea of fine-grained, flexible cognitive, or epistemological units is also the core of the current PER *resources framework* (Redish, 2014), in which the units are referred to as *resources*[8]. 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). It was proposed as a way of theorizing PER, which has historically often attended to observations of students and the teaching practice, but more rarely to the mechanisms of the science, that is, the theory of the teaching and learning of physics (Redish, 2014). Heron (2018) argues that there are several reasons why researchers in physics education research have not engaged more with education theories: The way physicists perceive education theories (e.g. prescriptions of best practices), that we are skeptical toward frameworks that makes the analysis too narrow or that there is a lack of consensus about the "status of the broad conceptual framework […] that has provided us some loose guidance" (2018, p. 12).

The concept of a resource originates in the work of Hammer (2000) as a response to the limitations with the the concept of misconception: Misconceptions do not provide "an account of productive resources students have for advancing their understanding" (Hammer, 2000, p. S52). Additionally, research on so-called misconceptions cannot explain the contextuality of students' ideas or the underlying mechanisms of students' difficulties. The central concept, the resource, is a metaphor from computer science: "a chunk of computer code that can be incorporated into programs to perform some function." (Hammer, 2000, p. S53). A resource can be defined as "an isolated, independent productive idea" (Wittmann, 2018, p. 2).

Similar to theories on dual processing, that model cognition as fast or slow (e.g. Kryjevskaia, Heron, & Heckler, 2021), Hammer (2000) relates resources to a fast and a slow process: The process of finding a useful resource is fast when encountering a familiar problem, and slow when encountering an unfamiliar problem as you need to "search through your resources, perhaps trying several of them out before you arrive at those you find useful" (Hammer, 2000, p. S53). It is possible to have several resources active at the same time during a slower process and the goal is then to reconcile conflicting ideas or to bring the activated resources together into something that is coherent. Hammer

[8] The resource is a cognitive construct. A physical object can not be a resource in its own right. A resource is first employed, or in the terminology of Redish (2004), activated, 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.

(2000, p. S53) provides an example of this through a problem involving a box, in a stream of water, that changes its temperature depending on the temperature of the water (in addition to factors such as an internal source of energy, etc.). This is compared to a box in a "stream" of sunlight and the task is to come up with what the temperature of the box is if "the box is cooler than that temperature the effect of the sunlight is to warm it, and if the box is warmer than that temperature, the effect of the sunlight is to cool it" (Hammer, 2000, p. S52). There are two possible conflicting resources that one can activate: "sunlight can only add energy" and "thermal equilibrium". The reconciliation involves figuring out what the flaw is with one of the types of reasoning in this particular context. As Hammer (2000) writes, the flaw is not in the resources themselves but rather in how they are applied and reasoned with: The box in the problem, "bathing" in sunlight can be thought of as being in constant thermal contact with an electromagnetic field but it is not in an equilibrium so the flaw lies in how thermal equilibrium is applied in the reasoning.

Hammer (2000) describes two types of resources: *conceptual* (resources related to conceptions for understanding something) and *epistemological* resources (beliefs about what it means to know something) and argues that just like how misconceptions have been studied and viewed as stable constructs that can be replaced (contrasted against conceptual resources), there could be a view that there are "misbeliefs" (as contrast with epistemological resources) about the have been viewed as stable constructs that can be replaced. I will use both conceptual and epistemological resources as concepts in my work. Epistemological resources are related to metacognitive skills as they both involve thinking about the nature of something.

Hammer (2000) uses the term "productive" in relation to resources but never really defines it. 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, for the purpose of the specific teaching situation, sound answer, then the resource is said to be *productive*. What productive means is rarely explained in research using a resources approach. An alternative to the previous definition of "productive" has been offered by Harrer (2013) who had noticed that "productive" often is used without a definition. He therefore, based on previous use of the term, proposed two types of productiveness: disciplinary productiveness and situated productiveness. The definition of the former is "the appropriate activation in a particular context, as judged by the community of physicists via the instructor or researcher" (Harrer, 2013, p. 43) and the latter is based on students' progress (here Harrer uses a quote from previous research): "There is productivity if one can discern significant disciplinary progress from the beginning to end of students' engagement with a particular issue" (Engle, 2012, p. 167, reformatted). Later research (Goodhew et al., 2018) using a resources approach has built on the definition of situated productiveness by describing the criteria for this type of productiveness as if the resource plays a part in the group's (or individual's) evolving thinking.

The Resources framework, as presented by Redish (2004, 2014), 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 person, 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) can 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* (see Figure 2): 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 "students' perception of the sociocultural environment […] affects that students' behavior" (Redish, 2014, p. 543).

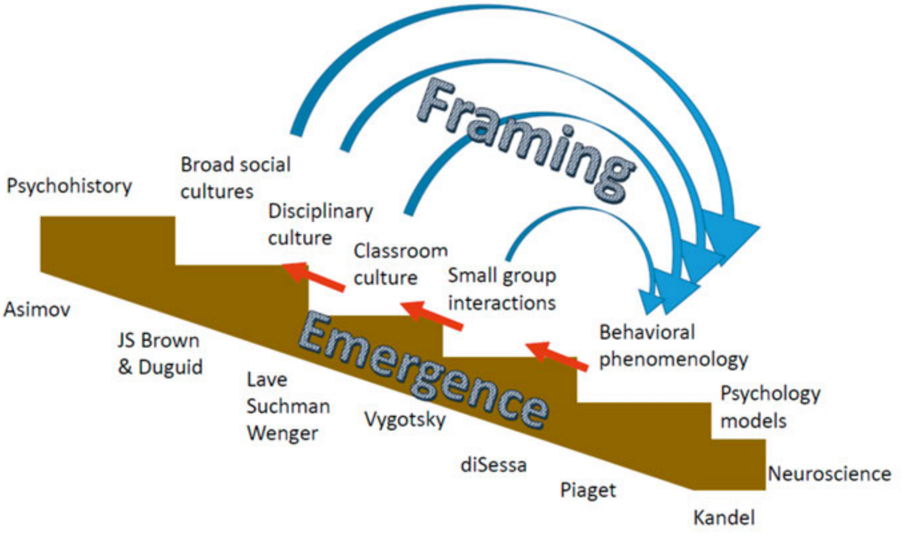


*Figure 2. The figure is based on the grain-size staircase as described and illustrated by Redish (2014). My research mainly involves levels between Piaget and Lave/Suchman/Wenger.*

The Resources framework draws on the idea of *framing*[9] from anthropology (Goffman, 1986) to describe the students' interpretation what a situation is about (Redish, 2014). The concept describes how knowledge is situated or contextual, just like Lave (1988) proposed in her work. 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 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 might 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 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 meters. 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 et al., 2015; van de Sande & 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

[9] The notion of framing has been adopted in several different traditions. I draw from the interpretation of the resources framework (Redish, 2004), with a focus on students' framing. In this tradition, framing relates to selective attention (Wood & Simons, 2017) and builds on Goffman's (1986) concept. A frame here is similar to a mindset (French II, 2016). This contrasts with social semiotics in which framing is more closely associated to what boundaries that semiotic systems (modes in the original terminology) can set for some elements of, for example an image (e.g. see van Leeuwen, 2005).

the relevant practice or behavior is in 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 *cognitive resources* as she *frames* a situation in a certain way. There are fine-grained resources that can 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 can be associated to a certain resource or resources, which affects the conceptual framing that is applied to the situation. This can 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 3, an individual encounters a situation that is framed as 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 that are 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.

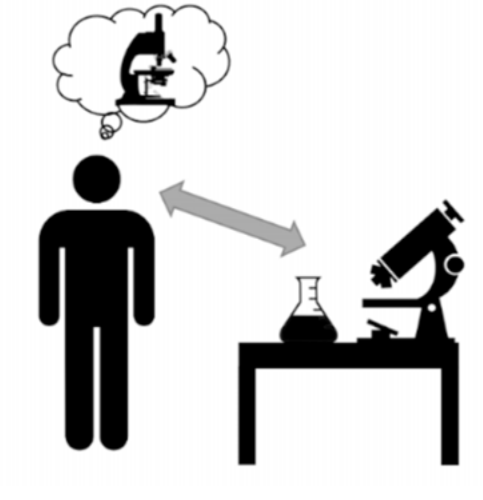

*Figure 3. An individual is trying to make sense of a situation through framing and applying cognitive resources that depends on the contextual factors that are noticed as being important.*

It has been argued that the paradigm of conceptual change has matured and that it now includes many more topics than just the discrepancy between formal knowledge and everyday knowledge (Amin et al., 2023). The response to early conceptual change models like the GMCC points at the problem with describing all students' conceptions as stable and that what is considered a misconception in one context is a misconception for all contexts and that it thus needs to be replaced or removed somehow. It is not completely clear that this is the idea that Posner et al. (1982) had in mind when they wrote their paper. But their use of the rejection of ideas in research programs as analogy to how the conceptual ecology (Toulmin, 1972) of humans change, i.e. Lakatos (1970) model of how research programs change, points toward this intention. Conceptual change is, however, a very broad paradigm and even models that promote a context-dependent view are included in the paradigm (Potvin et al., 2020).

There are ideas from the GMCC that still are compatible with the resources framework. It is, for example possible for cognitive conflicts, a sort of crisis, to occur even though the activated resources are generated "on the spot" and depend on the context. It is also possible to talk about misconceptions but a misconception is, in accordance with the resources framework, described as "a knowledge structure that is activated in a wide variety of contexts, is stable and resistant to change, and that disagrees with accepted scientific knowledge" (Redish, 2004, p. 57), in other words, a potential misconception must be identified across several contexts before it can be described as a misconception. The important difference between the traditional epistemology of conceptual change (like in the GMCC) and the more modern ideas, such as the resources framework, is that we no longer think of students' ideas as something can be "removed", "rejected" or "deleted" and that it can be more fruitful to identify the ideas that students already have in order to leverage them for teaching physics. The idea about cognitive conflict is thus no longer about getting proof that can lead to a rejection about ideas (Heron, 2018) but about a potential crisis that can be dealt with through students' already established ideas.

## 2.3 Social semiotics

*Social semiotics* is the second framework that I integrate in my synthesized framework. It is essentially about the signs and symbols that we create and interpret. In other words, it is about the representations that mediate some meaning.

There have been different variants (Bezemer & Jewitt, 2009) of social semiotics proposed since Halliday's (1978) first use of the term. One of the early proposals of social semiotics was offered by Lemke (1990). Lemke refers to social semiotics as a theory on "how human beings make sense of and to one another: how we make meaning" (1990, p. 183). The epistemology of social semiotics is closely related to that of *social constructionism* in philosophy (cf. Wittgenstein, 1968) and the *sociocultural approach* (e.g. Wertsch, 1993) in education research, through the focus on how we *make meaning* in social contexts and the emphasis on language as a tool.

Social semiotics can also be contrasted with traditional *semiotics* (e.g. Eco, 1979; Peirce, 1931) where signs are the focus of study:

> Traditional semiotics likes to assume that the relevant meanings are frozen and fixed in the text itself, to be extracted and decoded by the analyst by reference to a coding system that is impersonal and neutral, and universal for users of the code. Social semiotics cannot assume that tests produce exactly the meanings and effects that their authors hope for (Hodge & Kress, 1988, p. 12)

In other words, the meaning making in social contexts is central to social semiotics.

Social semiotics is a form of inquiry which is not self-contained. It requires a field which it can be applied to (van Leeuwen, 2005). One of the variants of social semiotics that applies the theory within a context is that of Airey and Linder (2017). Their variant focuses on the range of semiotic resources, such as diagrams, mathematics, spoken language and graphs, that are used in university physics education (and related fields). They define social semiotics as "the study of the development and reproduction of specialized systems of meaning making in particular sections of society" (Airey & Linder, 2017, p. 2), and add that their social semiotics is about how physicists share and make meaning through semiotic resources. In contrast to previous variants of social semiotics, Airey and Linder (2017) include science specific tools like laboratory apparatus in their variant of social semiotics. Physical objects such as laboratory apparatus have not really been emphasized in early research on meaning making and social semiotics (Tang et al., 2022), even though they are an important aspect of science lab education. There is, however, a growing body of studies (e.g. Volkwyn, Airey, Gregorcic, & Heijkenskjöld, 2019; Volkwyn, Gregorcic, & Airey, 2020; Volkwyn, 2020) that has followed the variant of Airey and Linder (2017) and that emphasizes lab tools from a social semiotics approach.

Social semiotics provides a range of different concepts in order to analyze and describe situations in which people make meaning. I will elaborate on the concepts that are central in my research below.

### 2.3.1 Semiotic resources, semiotic systems and tools

The first and most central concept to my studies is that of *semiotic resource*. The concept was originally coined by Halliday (1978) to refer to grammar as a resource that makes meaning, in contrast to the traditional view of grammar as a set of rules for producing correct sentences. van Leeuwen (2005), and researchers using the social semiotics approach after him, extends "grammar" to also include other modes of communication than spoken and written language. van Leeuwen (2005) describes semiotic resources as what has traditionally been called *signs* and Airey and Linder (2017) compares semiotic resources with what is commonly referred to as *representations* in physics education research. However, semiotic resources include languages, mathematics, graphs, but also laboratory apparatus, which would not be considered representations in a traditional sense (Airey & Linder, 2017). A socially organized set of semiotic resources (e.g. colors, graphs, etc.) is referred to as a *semiotic system* (sometimes referred to as modes) (Jewitt et al., 2016). The semiotic system can thus be thought of as a category of semiotic resources.

There has been a growing concern (e.g. Bernhard, 2018; Tang et al., 2022) for the lack of focus on laboratory equipment and physical objects in studies on meaning making from a social semiotics approach. Research based on social semiotics can respond to this concern through its emphasis on semiotic resources and semiotic systems. van Leeuwen (2005) outlines three things that researchers in social semiotics do:

1) Catalogue, document and identify semiotic resources.

2) Investigate the use of, and how people talk about semiotic resources in cultural and institutional contexts.

3) Investigate new semiotic resources and the use of known semiotic resources.

It could thus be argued that the semiotic resource is the center of attention for research based on social semiotics.

Several types of semiotic resources have been discussed in previous research. It has been discussed whether e.g. colors (e.g. Kress & van Leeuwen, 2002), lab devices (e.g. Volkwyn, 2020) and the sense of touch (e.g. Bezemer & Kress, 2014) can be considered as semiotic resources.

Social semiotics deals broadly on how meaning is made through semiotic rersources, but does typically not focus on physics or science education or even general education research. However, with the introduction of a social semiotics that targets physics education (Airey & Linder, 2017) and research journals focusing on education from a social semiotics perspective, such as Designs for Learning, it has become increasingly popular in education research.

Within social semiotics, there is also research (e.g. Tang, 2022; Volkwyn et al., 2019) on how meaning can be remade across different semiotic systems.

This is within social semiotics referred to as transduction, as opposed to translation that entails remaking meaning within the same semiotic system (e.g. Kress & van Leeuwen, 2002). Transduction can be exemplified with a Geiger counter which "transducts information about invisible radiation to an audible click" (Volkwyn et al., 2019, p. 17). It has been argued (Volkwyn et al., 2019) that transduction is a sign of learning as it demonstrates a learner's understanding of the meaning that is transduced

In my research, I refer to all objects, actions and representations in the learning environment that students interact with or talk about as semiotic resources, i.e. whatever students attend to in the learning environment. Eriksson et al. (2014) refer to this process of attending to or focusing on some aspects as *discernment* and describe it as an important competency when entering a discipline (disciplinary discernment).

When the semiotic resource is the unit of analysis in education research, it is common to ask research questions similar to "What meaning can this resource convey and how is that meaning constructed by students?" (Airey & Linder, 2017, p. 6). One way of approaching the question within social semiotics is to analyze the *affordances* (Gibson, 1979; Norman, 2013) of semiotic resources or semiotic systems.

I will sometimes use the term *tool*. In my use of the term, tools are one or several *semiotic resources* (collections of *semiotic resources*). An infrared (IR) camera can be used as an example: The IR camera is a tool that also can be described as a collection of semiotic resources (depending on how it is used): As an example two semiotic resources that can be identified through students' discussions and their dynamic use of the cameras, are the color red and a smartphone form (Samuelsson, 2020). In this case the IR camera is a tool which is also a collection of semiotic resources.

### 2.3.2 Affordances of semiotic resources and semiotic systems

Gibson (1979) introduced the concept of an object's *affordance*: "The *affordances* of the environment are what it *offers* […] what the object affords us is what we normally *pay attention to*" (Gibson, 1979, p. 127, 134, italics added) based on gestalt psychology. Gibson's concept is thus similar to the concept of *discernment* (how to attend to something and assign meaning to what we attend to (Eriksson et al., 2014)) and the way I use the concept of *semiotic resource* (i.e. what we pay attention to by talking about it or interacting with it).

The affordance "[…] points both ways, to the environment and to the observer" (Gibson, 1979, p. 129) and is therefore non-dualistic, i.e. the mind and the environment are not treated as two separate objects of analysis, according to Gibson's view. He 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 3 affords some kind of physical analysis and optical enlargement (affordance of the microscope), but the beaker also affords drinking (although many would probably frame it as hazardous to drink from a lab beaker), 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, 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 3 might still be that of enlargement (as the person might 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, affordance is a function-user-based concept and for most people, for example, 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 is the main function that the semiotic resource has in mediating some meaning for a specific situation. Affordances do not thus have to be directly related to possible physical actions, but could also involve possible thoughts and feelings. Affordances are made visible in how participants act and talk in a situation. The affordance of a semiotic resource can change with the context, e.g. the color red and the form of a heart can 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). I will also write about the affordance of a tool but this affordance is really an affordance emerging from one or several semiotic resources.

The theoretical contributions of Norman and Gibson are however very general as they ascribe affordances of objects to interacting *agents* (Norman, 2013), or environments to *organisms* (Gibson, 1979). In physics education research, 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 Kress (2010) in the interpretation of affordance within social semiotics: Semiotic modes, or what I, in this thesis, refer to as semiotic systems and semiotic resources, “have different potentials, so that they afford different kinds of possibilities of human expression and engagement with the world, and through this differential engagement with the world they facilitate differential possibilities of development” (Kress, 2000, p. 157).

The affordance is here related to culture, social aspects and materiality rather than perception. Building on this perspective, Fredlund, Airey & Linder (2012) propose a way to emphasize the social aspect of affordances via 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 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).

Included in this framework is, in addition to disciplinary affordance[10], 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.

### 2.3.3 Types of talk

Lemke’s (1990) social semiotics includes two theoretical constructs of communication, *thematic patterns* and *organizational pattern* or *activity structure* (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

[10] 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 latter 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.

spreads out” together with “temperature becomes the same everywhere” can 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.

There are other ideas that are not necessarily explicitly related to social semiotics but that, like Lemke’s (1990) research, deal with communication in classrooms and that also build on a sociocultural perspective. Like Lemke (1990), Mercer (1995) identified patterns of talk that students in classroom would engage in, and with a basis in the terminology of Barnes and Todd (1977), developed a typology of talk to describe these types of talk. Three types were proposed by Mercer (1995):

- *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.

The typology of talk has mostly been used as an analytical instrument to study younger students classroom talk but has in more recent years also been applied in physics education research (Andersson & Enghag, 2017).

It has been suggested that in particular exploratory talk is related to collaboration and that it “represents a distinctive social mode of thinking […] the embodiment of critical thinking, but […] also essential for successful participation in ‘educated’ communities of discourse (such as those associated with the practice of […] science)” (Mercer & Wegerif, 2001, p. 88). It has been argued (Wegerif, 2010) that aspects of exploratory talk such as taking on and challenging different viewpoints internally, can be important for more advanced human reasoning, i.e. it is dialogic. It has also been argued (Mercier & Sperber, 2011) that argumentative contexts are important for learning how to reason, contexts that historically used to be an essential part of being a university student in Sweden (Burman, 2012).

The epistemology behind both the work of Barnes and Todd (1977), and Mercer (e.g. 1995) is influenced by the work of Vygotsky (e.g. Mercer, 2008) and can thus be related both to the sociocultural structure of the resource framework (Redish, 2014) and the epistemology of social semiotics (e.g. van Leeuwen, 2005). However, Mercer and Wegerif (2001) argue that in contrast with their research, Vygotsky and most neo-Vygotskian research in psychology has avoided carrying out research within the authentic contexts in education, i.e. the classrooms.'

## 2.4 Toward the generalized resources triangle: A synthesis of ideas

With these frameworks and ideas about learning I can perhaps place myself in what Heron (2018) refers to as the intellectual domain and the social and cultural domain of physics education research. Some publications of this thesis lean more heavily into one of the two domains but the thesis taps into both domains as a doctoral thesis involves much more work than a single publication. I will here present the synthesis of the ideas from both of these domains.

Like Hammer (2000), I use the concept of a *(cognitive) resource* in two ways: To describe resources that are building blocks of what we think, i.e. *conceptual resources*, and resources that control how we think, , i.e. *epistemological resources*. These two types of resources will jointly be referred to as cognitive resources when needed (to distinguish them from semiotic resources). I will follow the terminology of Redish (Redish, 2004, 2014) and use "activate" for when a resource is generated (potentially from smaller fragments) and engaged with. When I refer to specific conceptual resources, I will describe them as ideas or larger resources, but there is an underlying assumption that these ideas are context-dependent in that they are generated "on the spot" from smaller resources, for example p-prims. My use of the concept of a (cognitive) resources is thus be closer to what Redish (2004) refers to as *patterns of association*. My research does not, however, go into detail about what these smaller resources are, but stays on the level where the ideas are used by the students in their reasoning (i.e. what is possible to interpret from their talk). It has been investigated what the fragments that constitute the larger patterns of associations, or resources, are, (diSessa, 1993) but that is not a goal of this thesis.

There are many examples of different particular conceptual and epistemological resources, of which I will just cover some that relate to my research. "Larger" (than p-prims, see the grain-size staircase (Redish, 2014)) cognitive constructs that I include under the concept of conceptual 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 different objects or events, e.g. a wide variety of exemplars, we are able to form abstractions of the classes or categories, called prototypes. This is a concept that was introduced by Rosch (1973) and can be described as the average of exemplars that forms a general representation for a category (e.g. Gärdenfors, 2004; Smith, 2014). However, I will treat exemplars and prototypes as the same conceptual resource in my thesis as the difference between the two types are not of relevance for my research. If I activate the conceptual resource of "when I dry my laundry" in order to reason about evaporation I could refer to one specific instance or memory of when I was drying laundry (i.e. an exemplar), but I could just as well be referring to some average of the many times I have been drying my laundry (i.e. a prototype). Both of the conceptual resources are specific in what situation they are about, no matter if it is one instance or an average. Other conceptual resources include conceptual metaphors (Lakoff, 1987; Lakoff & Johnson, 1980) and phenomenological primitives (diSessa, 1993), but also concepts, theories and principles from science that are not explicitly related to a specific situation in which they were taught. There are also other cognitive units that could be considered to be conceptual resources but that are not involved or not as prominent in my research, for example ontological categories (e.g. Chi, Feltovich, & Glaser, 1981).

The second type of cognitive resource is *epistemological resources*. These can be quite large in grain-size, such as a frame (Goffman, 1986; Redish, 2004) or a mindset (e.g. French II, 2016) that frames the whole approach to an activity, or smaller, like a heuristic (e.g. Heckler, 2011; Kahneman, Slovic, Tversky, & Kahneman, 1974; Talanquer, 2014), which can best be described as a type of "shortcut reasoning strategies" (Talanquer, 2014, p. 1092), often associated to quick or intuitive thinking. Additionally, what could be referred to as metacognitive skills, such as *self-regulation* (Zimmerman, 1986) and *metacognitive reflection* (e.g. Pintrich, Marx, & Boyle, 1993), are also considered to be epistemological resources. In addition, there are several other types of theoretical constructs that could be described as epistemological resources but that are not involved in my research, for example *epistemic games* (e.g. Tuminaro & Redish, 2007).

Throughout my research, I have brought ideas from both social semiotics and the resources framework together as analytical instruments when necessary: The concepts of resources and framing to deal with students' cognitive ideas and approaches to teaching activities, and the concept of semiotic resources to deal with how they communicate those ideas and interact with the tools and environment around them. In the last paper of the thesis (V), I made the integration more coherent by slightly modifying the ontology so that framing is described as an epistemological resource (which in turn affects the activation of other resources). However, it is described as a *mindset* in V. A mindset can be defined as a frame of reference that sets a restriction or limit to what type of thinking is done (Benson & Dresdow, 2003), which is similar to what is referred to as a frame in the resources framework (Hammer, 2000; Redish, 2004). I have decided to use *frame* to refer to this idea in this thesis as it follows the terminology of the resources framework more closely. Epistemological resources have been described as being closely related to one's epistemological frame in previous research (e.g. Richards, Jones, & Etkina, 2020). A frame in my synthesis of the frameworks is, in contrast to the frame in the resources framework, considered to be an epistemological resource.

When describing frames as epistemological resources, it is possible to use a full resources terminology where all the skills, ideas and attended tools and representations can be described as different types of resources based on the two frameworks social semiotic and resources framework. In the center of this synthesis is the student activity, i.e. what the students do and say together in the particular learning environment. The emphasis on the activity as a unit of analysis has been described as important for a reformulation in which both cognitive and sociocultural perspective can inform each other (Rogoff, 1995). The synthesis of ideas from social semiotics and the resources framework can be represented through the generalized resources triangle (see Figure 4), that I developed in V.

The generalized resources triangle can be used to model students' activity and the relations between conceptual, epistemological and semiotic resources students' activity. It is possible to model students' activity through an instantiated resources triangle (based on the generalized resources triangle) in which the specific identified resources that support a particular activity are placed in each corner (an example of this is provided in chapter 7). For example, the students' frame that students activate for a particular learning environment can be placed in the corner for epistemological resources, i.e. what the students in general do during a learning activity roughly corresponds to how the students think about the activity, and what resources that are involved in such activity. In Figure 4, it is possible to relate side a and b to the two frameworks of my thesis, the resources framework and social semiotics. Side a involves, for example, the activation of conceptual resources based on a frame, as described in the resources framework. Side b involves the meaning making with semiotic resources as described in social semiotics. Meanwhile, side c is a new relation that can describe aspects of students' activity where they mediate an epistemological resource through a semiotic resource, for example a frame through a type of speech which results in a type of talk. I believe that side c emerges from the synthesis and that it is not really described within the two frameworks.

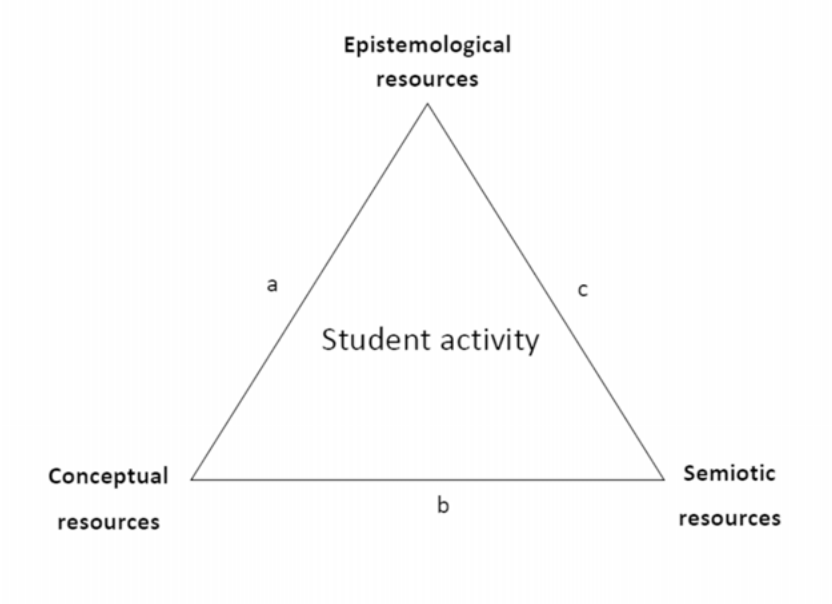


*Figure 4. The generalized resources triangle. The activity of students can be said to emerge from cognitive resources (conceptual and epistemological) that students activate and semiotic resources that students employ in the learning environment. Side a is represented in the resources framework, e.g. how students' framing affects the activation of resources. Side b is represented in social semiotics, e.g. how a semiotic resource is used for meaning making. Side c, however, has not really been explored before through the two frameworks.*

The resources framework acknowledges so-called misconceptions, but as Redish (2004, p. 57) defines it, a misconception is "a knowledge structure that is activated in a wide variety of contexts, is stable and resistant to change, and that disagrees with accepted scientific knowledge". In other words, many of the conceptual resources that previously have been thought of as misconceptions are likely not misconceptions as they are affected by slight changes in the context and what other conceptual resources that are activated for a specific problem (Hammer, 2000). Additionally, we know that it can be very difficult to obtain even minor conceptual changes (Dunbar et al., 2007). Misconceptions have also been shown to be generative in terms students' reasoning, i.e. that reasoning can be developed in response to contingencies involving misconceptions in a specific situation (Hamza & Wickman, 2008). However, there are instances of students, in a specific situation, encountering something that is conflicting, that distracts them or inhibits a certain type of reasoning (more on this in the licentiate thesis). I draw on the idea of *barrier* from Loverude, Kautz and Heron (2002) to acknowledge the resources that can lead to a, for the activity, challenging situation. Resources that acts as barriers can be inhibiting, in conflict with other resources or distracting (this construct was proposed in my licentiate thesis). The difference between the two types of productiveness defined by Harrer (2013), disciplinary and situated productiveness, can be illustrated with the concept of a barrier: a barrier can be productive if one uses the definition of situated productiveness as it can lead to some progress as encountering and dealing with barriers could progress students' meaning making: A cognitive conflict can lead to students refining their knowledge thus finding new meaning in the encountered situation. Additionally, research shows that, for the problems provided, incorrect guesses do not affect recall performance of factual knowledge (Kang et al., 2011). In fact, encountered errors, followed by corrective feedback can results in improved learning compared to if the error had not been encountered (Huelser & Metcalfe, 2012). It is therefore important to be aware of how barriers are dealt with, both from an instructor perspective and a student perspective, i.e. when considering if a lab should be designed in such a way that students encounter as few barriers as possible. But a barrier might not be productive if one applies it to the idea of *disciplinary productiveness* (it then depends on the instructor or researcher). I will follow the progress perspective on productiveness in this thesis but I, like other researchers, have used other definitions (or no definitions at all). This is because when *productive* is used in relation to previous studies, I then use it as it is used in those studies.

This chapter has elaborated on two frameworks important for my research, social semiotics and the resources framework. Additionally, I have presented my own theoretical constructs and the conceptual framework that I use in this thesis.

# 3. Previous research

This review of previous research consists of four parts: a presentation of research on the learning of thermodynamics[11], research on inquiry and lab learning environments, research on tools for inquiry in labs (with a focus on IR cameras) and students' making meaning in thermodynamics education. A more extensive review of research on thermodynamics education and visualization and education can be found in the licentiate thesis.

## 3.1 Learning of thermodynamics

This part of the literature review is a summary of work in *physics education research* (I will refer to the research field as *PER* here) on the learning and understanding of *heat*, *temperature*, *energy* and *thermodynamics*.

Three resources provide an 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 concept of energy (e.g. Meredith & Ruzycki, 2019). They constitute the core from which the majority of the papers in this review are taken.

The branch of physics called *thermodynamics* includes 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?" and "How is it possible to increase the temperature of a sheet of paper with just a glass of water at room temperature?". More formally: Thermodynamics is a branch of both physics and chemistry (and engineering) that involves concepts such as heat, work, temperature, and energy. Physics, chemistry and engineering all have slightly different foci, type of problems and ways of describing thermodynamics (Christiansen & Rump, 2008) but they all share the central concepts and laws. In particular, the concept of energy, and related concepts such as enthalpy and Gibbs free energy, have been suggested to be important for interdisciplinary

[11] 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* (central for the previously mentioned concepts of enthalpy and Gibbs free energy).

education in science to facilitate discussions across physics, chemistry and biology (Redish et al., 2014).

The research on learning and understanding of concepts, such as energy and heat, has been a part of PER since the early days of the field (McDermott & Redish, 1999) and even contributed to the development within the paradigm of conceptual change (Erickson, 1979; Posner et al., 1982). Much of the current research in PER that concerns the sub-field focuses on the learning and understanding of the concept of energy.

The primary concepts involved in thermodynamics can be described through the *laws of thermodynamics*: Roughly, 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.[12]

### 3.1.1 The concepts of heat and energy

My research concerns the concept of energy in relation to heat, temperature and phase transitions and 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 comes from 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 process of transferring energy by means of temperature differences between multiple systems. 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 (Brookes & Etkina, 2015). Brookes and Etkina (2015) describe 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 can be confusing for 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 introductory courses at university level (e.g. Erickson, 1979; Greenbowe & Meltzer, 2003; Warren, 1972). Müller (2007) describes a historical experiment that still has influence on todays thermodynamics: An experiment in the 18$^{th}$ century led physicist Joseph Black to introduce the term *latent heat* for the quantity of heat required to melt ice at constant temperature.

[12] The third law deals with the special case of absolute zero.

Latent heat is still a common technical term used for the amount of energy required or released during phase transition. The term might however strengthen the belief that heat is a substance that is "hidden" or latent within a material.

The energy concept is a difficult concept to grasp. As Feynman puts it:

> […] 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 et al., 1989, pp. 4–1)

At the same time, it is also a fundamental concept for all the science disciplines. 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. *The Next Generation Science Standards* (NGSS) (NGSS Lead States, 2013), that were adopted in the USA 2013, outlines the energy concept as a cross cutting idea. This emphasis can also be found in the European science standards such as the *German science standards* (Kubsch et al., 2019) or the *Swedish syllabus for physics* in high school education (e.g. 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 et al., 2018; 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 chemical bonds form or break. In another paper, Dreyfus et al. (2014) proposes a way for teaching *chemical energy* in a coherent way across physics, chemistry and biology.

According to Kesidou and Duit (1993), physicists conceptualize energy as 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 Hechts (2019), many physics textbooks do not directly define the concept but choose to rather avoid 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). Duit (1984) describes basic aspects that relate to the energy concept and claims that they facilitate an 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 might support the understanding of energy conservation and energy conservation often contradicts everyday experience.

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 might equate heat with temperature or think of temperature as a measurement of heat (Erickson, 1979; Warren, 1972). It has also been shown (Brookes et al., 2005; Hecht, 2019; Leite, 1999; Summers, 1983; Warren, 1972; Zemansky, 1970) that textbooks are particularly poor at explaining heat or giving definitions for the concept that help students in distinguishing heat from temperature. If textbooks give poor explanations, with students tending to keep their initial ideas about heat and energy after physics instruction (Duit, 1981). If temperature being thought of as a measurement of heat, then perhaps we have to begin considering what the initial ideas about heat are for learners. This is the topic of the next section of the literature review.

### 3.1.2 Personal experiences in learning about heat and energy

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 used today as a metaphor in teaching the concept of energy (e.g. Scherr, Close, McKagan, & Vokos, 2012) and by physicists talking about energy (Amin, 2009) or heat as in "heat is transferred from A to B" (Brookes & Etkina, 2015, p. 765). The metaphor of energy as a substance 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 this supports the understanding of the conservation of energy (which is leveraged in teaching activities such as *Energy Theater* (Daane, Wells, et al., 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.

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 a spring is compressed (it can feel exhausting). But how do students understand these experiences? Clough and Driver (1985) show that students tend to use their *bodies* as a reference when they reason about the direction of conduction of heat which makes it difficult for them to relate what they feel as cold to the conduction of heat. Misinterpretations of heat transfer results in difficulties understanding how matter that changes 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 can have a temperature of 2000 degrees Celsius. Objects with different *thermal conductivity*, but the same temperature, are perceived as having different temperatures as the learner uses their *sense of touch* as an indication of the temperature of the object, thus misinterpreting the experience. In regards to this confusion, Erickson (1979, p. 59) 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".

Several activities for teaching about the energy concept have been proposed by Scherr and colleagues, for example *Energy Theater* (Daane, Wells, et al., 2014; Scherr, Close, Close, et al., 2012), *Energy Cubes* (Scherr, Close, Close, et al., 2012) and *Energy Tracking Diagrams* (Scherr et al., 2016). All these activities reinforce 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.

Similarly, *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 transfer to another object (spring), and then transforms 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 finish in one image.

## 3.2 Inquiry-based lab learning environments

The purpose of the lab in education has been discussed for some time (Hofstein & Lunetta, 1982, 2004; Trumper, 2003). More recently there has been a call for reforming labs so that they focus on teaching lab skills rather than on reinforcing concepts (Holmes & Wieman, 2018; Wieman & Holmes, 2015) as results from previous studies suggests that lab activities are poor at reinforcing content (Holmes & Wieman, 2018). These labs skills involve technical and practical skills (the analysis of data and the use of equipment), cognitive decision-making skills (e.g. what data to collect) and metacognitive skills (e.g. thinking about thinking) (Holmes & Smith, 2023). Additionally, labs that focus on students' development of lab skills lead students to have attitudes about experimental physics that are more expertlike than if the labs focus on conceptual understanding (Wilcox & Lewandowski, 2017). The dichotomy is here between lab skills and conceptual reinforcement. From my point of view, however, a more important issue is how we engage students in lab education. To investigate this question we first need to address what types of labs, in terms of openness, students are to engage in.

There has been a debate (e.g. Hmelo-Silver et al., 2007; Kirschner et al., 2006) about whether learning activities involving minimally guided approaches are more effective than traditional instructed teaching activities. This points to a problem with the terminology used for these types of activities.

### 3.2.1 The debate on instructional approaches

Kirschner, Sweller, and Clark (2006, see page 75) describe a set of different instructional approaches or teaching methods; inquiry learning; problem-based learning; constructivist learning; experiential learning and, discovery learning, as minimally guided instructional approaches. They argue that there is a fundamental problem with these approaches because of the demands that they put on the learner in terms of doing and learning things on their own. Based on research on human cognitive architecture, they argue that minimal guidance in learning leads to a large demand on the working memory, i.e. a larger cognitive load, in particular when it comes to problem solving (Sweller, 1988). The targets of their critique are the progressive ideas of Bruner, Piaget and Dewey that represent the trend of, what is often referred to as, discovery learning – like inquiry-based learning and problem-based learning, a constructivist method, that unlike inquiry- and problem-based learning often involves minimally guided instruction (Hmelo-Silver et al., 2007). This type of minimally guided learning activity has been critized for causing too much cognitive load for students if they do not have “sufficiently high prior knowledge to provide “internal” guidance”(Kirschner et al., 2006, p. 75) about what they are learning about.

As a response to this critique, Hmelo-Silver et al. (2007) point out two flaws of the critique. Firstly, that the different instructional approaches that are categorized as minimally guided learning are guided to different degrees and not a uniform category of approaches. Inquiry-based learning and problem-based learning are in particular argued to involve extensive guidance for students. Secondly, they show that there is empirical evidence for the benefits of using an inquiry-based instructional approach. They do, however, agree with Kirschner et al. (2006) when it comes to the problems with unguided learning.

A contemporary review (Mayer, 2004) of research on unguided teaching approaches[13] reached a conclusion similar to that of Kirschner et al. (2006). There is a difference between what the authors of the two papers argue though: Although Mayer (2004) argues against pure discovery learning or unguided approaches, he carefully points out that these approaches are sometimes framed as constructivist approaches even when this is not the case. Additionally, it is suggested that

> the constructivist view of learning may be best supported by methods of instruction that involve cognitive activity rather than behavioral activity, instructional guidance rather than pure discovery, and curricular focus rather than unstructured exploration.
> (Mayer, 2004, p. 14)

In this case, behavioral activity involves activities that, in a direct way, students can be observed doing (e.g. hands-on activity or discussions). Cognitive activity involves processing of knowledge (e.g. organization and integration of knowledge) that is not always observable. Mayer (2004) also adds that discussions can be beneficial depending on how well the discussion promotes cognitive processing, it is just that it is the cognitive activity that should be emphasized when it comes to teaching approaches. Other research in educational psychology and linguistics (Mercer, 2013; Mercer & Wegerif, 2001) suggests that talk is a social mode of thinking, and thus discussions can reflect cognitive processing.

[13] Mayer (2004) refers to this as pure discovery (see page 17).

### 3.2.2 Relating active engagement to inquiry and curiosity

We take terms such as active engagement and inquiry for granted, it is rare that they are defined and they are easily misunderstood (as Hmelo-Silver et al. (2007) points out in the debate). There have been attempts to clarify how the different labels for guided and less guided activities relate to the structure of the learning activities. Buck et al. (2008) have developed a rubric that can be used to characterize the level of inquiry of labs through different aspects that are provided to students or not in labs (see chapter 3.2.4).

Active engagement is a topic in education research that sometimes[14] (e.g. Anthony, 1996; Bernhard, 2000; Cranton, 2012) is described as being based on the same fundamental ideas as inquiry-based learning (i.e. constructivism) and involves many types of activities including problem-solving, tutorials and worksheet exercises (Freeman et al., 2014) in which students have to interact with something. An activity or teaching method can involve active engagement without necessarily being inquiry-based, for example Just-in-Time Teaching (Novak et al., 1999), which focuses on relating preparatory homework to classroom activities through feedback. We know that active engagement is important for learning (Freeman et al., 2014), but there are two ways of being active: physically and mentally (sometimes referred to as hands-on and minds-on). To be active (in active engagement) mainly means to be active in terms of the mind (Dehaene, 2021), but this can also involve being active physically, in particular in collaborative activities when one has to share the mental activity with others through semiotic resources in the environment.

Previous research has emphasized the importance of laboratory activities being "minds-on" (e.g. Ho, Elmgren, & Karlsson, 2015; Hofstein & Lunetta, 2004) in addition to being "hands-on". It is possible to come up with situations where one is physically active with an activity without being mentally active, i.e. without actively relating the new experience to previous experience and thus making meaning, for example in routine activities like when preparing food that you already know how to prepare. Holmes and Wieman (2018, pp. 40–41) describe this mental passivity in a physics lab context: "Although the students are going through the motions of physics experimentation, their brains are not engaged in the process, and there is little need or reason to think about the physics content involved". Additionally, previous research has suggested that students in cookbook labs have fewer episodes of meaning making than students in more open labs (Karelina & Etkina, 2007; Lippmann, 2002), so it should be expected that more open labs involve more active engagement.

Thus, students can be active in a variety of ways: They can be active in the mind (by actively processing information), in talk, or with their bodies. However, it has been argued that the "active" of "active engagement" does not have to involve the body's movement but that it is the activity in the brain that is

[14] It has been argued that constructivism is a model of learning which does not necessarily relate to any model of instruction in particular (Millar, 1989).

important (Dehaene, 2021). This is in line with what Mayer (2004) argued: that the chosen instructional approach should promote primarily cognitive activity rather than behavioral activity. It has, however, been argued (Tang et al., 2022) that there is a certain blurriness between behavioral activity and cognitive activity as behavioral activity, or manipulation of physical objects also involves idea generation.

Active engagement relates to *curiosity* (Dehaene, 2021), an aspect which has been described as central to the vision of NGSS (Robertson et al., 2019). Curiosity can be related to interest (Luce & Hsi, 2014) as curiosity can foster interest (Engel, 2009) but curiosity can be described to be, in contrast to interest, more spontaneous, i.e. something unexpected that one did not have any prior interest in can arouse one's curiosity. One's curiosity can for example be piqued by encountering unknown and exotic ideas (Engel, 2009), i.e. that which is not known and that one therefore can not have any prior interest in. Luce and Hsi (2014) elaborate on what interest is: One can be interested in different topics of science but that does not necessarily mean that one is interested in the practices of science.

In research, there have been slightly different views of what piques someone's curiosity: *uncertainty* that leads to some sort of excitement, or arousal, and subsequent exploration (e.g. Berlyne, 1954), when one experiences stimuli that do not fit one's conceptual (cognitive) system that represents one's previous experience (Beswick & Tallmadge, 1971) and *novelty* (Piaget, 1952). Beswick and Tallmadge (1971) have argued that situations that lead to conceptual conflicts arouse curiosity for those that already are curious but deter those that are not already curious. In general, previous research (M. J. Kang et al., 2009; Kidd et al., 2012) suggests that curiosity is aroused only by something that is not too novel or too familiar, or in other words; "curiosity is not directly related to the degree of surprise or novelty but instead follows a bell curve. […] We have no curiosity for the unsurprising […] But we are also not attracted to things that are too novel […] or so confusing that their structure eludes us" (Dehaene, 2021, p. 190). It has been argued (Engel, 2009) that fostering curiosity begins with teacher training and that we therefore need to provide teacher students with opportunities to expand their own curiosity. Curiosity has also been shown (Stumm et al., 2011) to be a core determinant of academic achievement.

The research on curiosity in science has mainly been carried out on children (Levrini et al., 2017) and curiosity is often neglected in early physics education at many universities even though research (Levrini et al., 2017) has argued that introductory labs could be used as opportunities to pique students' curiosities. Arousing curiosity requires that the student has the appropriate resources, however, and it is possible that a student can become "overwhelmed or distracted by too much information" (Arnone et al., 2011, p. 182). The consensus in research on curiosity is that curiosity relates to an exploratory behavior and there have been attempts over the years to describe what this relation is (Arnone et al., 2011). Loewenstein (1994, p. 76) offers an account of curiosity that involves viewing "curiosity as a form of cognitively induced deprivation that results from the perception of a gap in one's knowledge". This is similar to the core of the conceptualization of learning offered by Wickman and Östman (2002) and later Lidar et al. (2005): When students find themselves in situations where something is not immediately intelligible (nothing *stands fast*) there is a *gap* that needs to be filled with similarities and differences to previous experience, i.e. the construction of relations. Learning is here related to meaning making and curiosity and thus also active engagement.

The term "active" can be somewhat vague when one thinks about what it does not involve, i.e. passive learning, and in what situations students passively learn something. In most literature, active engagement or inquiry methods are contrasted with, what is often referred to as, standard or traditional methods (the common terms used in this type of research , e.g. Deslauriers et al., 2011; Wieman, 2014) which usually involves the teacher teaching through a direct approach in which the subject matter is presented and explained to the students that are "primarily listening and taking notes" (Wieman, 2014, p. 8319).

### 3.2.3 Active and systematic engagement

This thesis mainly focuses on students that participate in labs, in particular experimentation, and how active students are thus becomes a question about how much they interact with the material that is available to them and how much they discuss what they are working with, i.e. their engagement with the lab activity in terms of self-initiated practice and communication. Meaning making is directly related to active engagement as active engagement primarily is mental (Dehaene, 2021) and meaning making involves relating encountered experiences with previous experience. However, active students are not necessarily systematic. Systematicity in physics is related to critical thinking (Nygren et al., 2018) and thus the practice of lab skills (Holmes et al., 2015; Walsh et al., 2019, 2022)

Zwickl et al. (2023) have looked closer at the traditional lab by characterizing it through activity theory (e.g. Engeström, 2001), which involves characteristics such as tools, rules and outcomes. They describe traditional labs as using "highly procedural lab guides […] that reduces demands on working memory (attending to one step at a time) and prior knowledge (the instructor already decided how and why to do the experiment)" (Zwickl et al., 2023, pp. 10–10). This is similar to the argument (Kirschner et al., 2006) that more direct labs are more effective than unguided labs because they reduce students' cognitive load compared to the unguided labs. However, Zwickl et al. (2023) bring up an important point, that there are conflicting goals in traditional labs as they are supposed to both replicate the scientific process and scientific results. While the former (reducing the demands on working memory) is best achieved through a direct and linear process, the latter (replicating an authentic research process) requires much more time and can be highly nonlinear without a clear outcome (i.e. the opposite of what a direct instructional approach provides). By employing a direct instructional approach, it is possible to encourage students to be active and systematic, but this does not allow the students to actually practice being active and systematic on their own initiative in an authentic, or close to authentic, research process.

There are many different types of methods and learning environments that allow students to, in contrast to traditional labs, investigate phenomena in labs on their own at different levels of inquiry, for example problem-based learning, inquiry learning and unguided discovery learning. All of these methodologies could be said to be based on the idea of progressive education, that learners should experience, or do things, on their own to some degree, e.g. the epistemologies of Montessori (1912), Piaget (1970) and Dewey (1964).

Inquiry-based labs can have different degrees of openness (which will be covered later in this chapter). The ideas of the early developers of constructivist learning methods might seem more radical than what results in practice as the early proposals of constructivist teaching methods sometimes involved free discovery without any guidance. For example, Piaget claimed that "each time one prematurely teaches a child something he could have discovered for himself, that child is kept from inventing it and consequently from understanding it completely" (Piaget, 1970, p. 715).

The early developers did have some ideas in common with modern research in cognitive science about active students (Dehaene, 2021): That active engagement is primarily mental. For example, Dewey (1964) argued that the student needs to be intellectually active and not merely a passive recipient of knowledge (Dewey used the analogy of a recording phonograph or the student being connected to a reservoir of knowledge through a pipeline passively receiving the knowledge). He argued that, a "mentally active scholar" (Dewey, 1964, p. 424) should be eager and willing when they learn, not reluctant and forced into learning something, i.e. interest and motivation are important components in learning, and that it is essential for thinking "to maintain the state of doubt and to carry on systematic and protracted inquiry" (Dewey, 2011, p. 14).

Dewey (1964) also stressed the importance of students actively applying, constructing and expressing their knowledge in new ways as it allows for the testing of their knowledge. This is done in for example labs, but labs are too often "of a merely technical sort, not a genuine carrying forward of a theoretical knowledge. It aims at […] driving home into memory of something already learned as a matter of mere information." (1964, p. 424). Based on these arguments, Dewey called for more project-based education, i.e. education that involve project work, which is another type of education that Kirschner et al.

(2006) argues as being too extensively committed to by educators based on constructivism.

There are many different types of curricula that aim to promote active engagement in physics education and that also have a basis in research (Bernhard, 2000; Buongiorno et al., 2021), for example *Peer Instruction* (Mazur, 1997), *Tutorials* (McDermott et al., 1998) and *Interactive Lecture Demonstrations* (Sokoloff & Thornton, 1997). McDermott and the Physics Education Group at the University of Washington (1996) were early in developing material (a set of lab-based modules called *Physics by Inquiry*) that explicitly involved inquiry-based learning activities. In Physics by Inquiry, students are to "develop basic physical concepts, use and interpret different forms of scientific representations, and construct explanatory models with predictive capability" (McDermott & The PEG at UW, 1996, p. iii). This is achieved by, for example, having the students record their work (e.g. observations) and reflect on their learning in a notebook during the modules. Because of the epistemological focus, the method is especially apt for teacher training according to the authors. There are several other methods and curricula that have been developed within physics education research over the years. However, there are two methods in particular that are of interest for this thesis as they have informed the research in this thesis (as probing methods): Prediction-Observation-Explanation (White & Gunstone, 1992) and Investigative Science Learning Environment (e.g. Etkina et al., 2021). These are described in more detail in chapter 5.

There are both case studies (e.g. Kapon, 2016) and large-scale studies (Freeman et al., 2014) that, in contrast with the concerns of Kirschner et al. (2006), show that active engagement or inquiry-based education lead to higher gains in terms of learning in physics, or that students in physics improve some of their inquiry skills (e.g. the skill to design an experiment) by participating in inquiry-based activities (e.g. Balogová & Ješková, 2018). However, as shown in a recent study (Deslauriers et al., 2019), students that participate in active instruction can perceive that they learn less than students that participate in a traditional lecture even though they actually learnt more. The authors of the study suggest that the students in active instruction might relate the effort and demands in the activity to low learning gains and warn that this can affect students' motivation in activities based on active instruction. Additionally, their results show that some students perceive the interruptions in active instruction (switching between group activities and involvement of the instructor) as a problem compared to the flow of a traditional lecture.

Basing the design of the learning environment on inquiry does not, however, necessarily imply that the students will be systematic. Systematicity require its own practice on tasks where students have to be systematic, i.e. open problems, in order for students to develop the high-level thinking skills (May & Etkina, 2002) or lab skills that can lead to a more systematic approach. There has been a tension between teaching for these high-level thinking skills, or lab skills, and conceptual reinforcement: The Framework for K-12 Education (National Research Council, 2012) describes how there always has been a tension "between the emphasis that should be placed on developing knowledge of the content of science and emphasis place on scientific practices" (2012, p. 41) in science education. As mentioned earlier in this chapter, there have been calls (e.g. Holmes & Wieman, 2018; Smith & Holmes, 2021) for focusing on the scientific practice (lab skills) rather than reinforcing concepts in lab education as previous research (Wieman & Holmes, 2015) shows that there is no measurable benefit in using labs that aim at reinforcing concepts at introductory level when compared to not using labs as a component of a course at all. According to the call, labs should not demonstrate concepts but should "showcase what it means to do experimental physics" (Smith & Holmes, 2021, p. 662). Holmes & Wieman (2016, 2018) interviewed a focus group of students about their thinking during lab work to understand why structured lab courses with a focus on content fail to meet the aims of the courses. The interviews revealed that there were two aspects that students thought about during their lab work: the analysis of data and finishing the lab on time. However, students have also described how it is important that they get to make decisions on their own, get time to reflect on the decisions and that they get time to fix and improve experiments, and that this is something that structured lab courses lack (Holmes & Wieman, 2018). In other words, students realize what studies (Wilcox & Lewandowski, 2016a), using the *Colorado Learning Attitudes about Science Survey for Experimental Physics* (*E-CLASS* (Wilcox & Lewandowski, 2016b)), have shown: That open-ended lab activities lead to more expertlike responses in postinstruction (compared to traditional lab activities).

### 3.2.4 To characterize lab learning environments

There have been attempts to characterize the level of instructional approaches such as discovery learning, confirmation labs and inquiry-based learning, by looking at what information is given, for each part of a lab activity, in the instructions and what parts of the activity the students could act independently in (e.g. Buck et al., 2008; Fay et al., 2007).

Schwab (1960) argued that labs are particularly apt for inquiry and that lab work should lead and not merely follow the rest of students' science education. Using the lab manual, Schwab described three levels of openness (see Table 2) of which, what he referred to as, the simplest and first level involved the manual providing the problems and information that "the student can discover relations he does not already know from his book." (Schwab, 1960, p. 187). At the second level, the manual provides problems but the methods and answers are not provided. And finally, at the third level, everything is open (problem, answer and method) and the student is just presented with a phenomenon to explore (Schwab exemplifies this with a student exploring a pendulum by playing with it until the student discerns a potential problem that could be investigated). Other researchers (Herron, 1971) have later expanded on Schwab's characterization or provided other rubrics that can be used to characterize labs in terms of openness (e.g. Holmes & Wieman, 2016).

*Table 2. The three levels of inquiry proposed by Schwab (1960).*

| | *Problem* | *Method* | *Answer* |
|---|---|---|---|
| *Level 1* | Given | Given | Open |
| *Level 2* | Given | Open | Open |
| *Level 3* | Open | Open | Open |

Banchi and Bell (2008, see page 27) describe a four-level continuum of inquiry:

- Confirmation inquiry (level 1): The problem, method and results are all given in advance, i.e. the students are to confirm the results for a certain problem with some given methods.

- Structure inquiry (level 2): The problem and method are given but the students have to come up with an explanation.

- Guided inquiry (level 3): The problem is given but both methods and explanations are left open for the students to design and make. The teacher still plays an important guiding part on this level of inquiry.

- Open inquiry (level 4): The level in which students are to act as scientists and come up with problems, methods and explanations, in addition to communicate their results, on their own. The authors describe this level as very demanding in terms of cognitive effort.

In contrast to previous authors, Banchi and Bell (2008) emphasize the importance of the first two levels at the early stages of students' education before they have developed the necessary abilities to deal with more open or unguided inquiry. Additionally, communication of the results was emphasized as an important component of the third and fourth level.

A more detailed characterization (of inquiry in lab education in particular) was proposed by Buck et al. (2008) through a literature review of college laboratory manuals and texts across multiple science discplines discussing or referring to inquiry. They identified six characteristics and five levels of which a level is "the extent to which a laboratory investigation provides guidance in terms of the characteristics" (Buck et al., 2008, p. 54). The final rubric (see

Table 3) allows for a more fine-grained characterization of inquiry-based activities (in particular labs) than previous ones.

Although not explicitly intended to be a way of characterizing openness in labs, Holmes & Wieman (2016) described the cognitive task elements of three levels of openness: Research, design lab courses and structured lab courses (see page 020103-9). The level referred to as research refers to undergraduate research and design lab courses involve students designing and carrying out experimental projects.

*Table 3. The characterization of inquiry-based lab activities proposed by Buck et al. (2008).*

| *Characteristic* | *Level 0: Confirmation* | *Level 0.5: Structured inquiry* | *Level 1: Guided inquiry* | *Level 2: Open inquiry* | *Level 3: Authentic inquiry* |
|---|---|---|---|---|---|
| Problem/question | Provided | Provided | Provided | Provided | Not provided |
| Theory/Background | Provided | Provided | Provided | Provided | Not provided |
| Procedures/Design | Provided | Provided | Provided | Not provided | Not provided |
| Results analysis | Provided | Provided | Not provided | Not provided | Not provided |
| Results communication | Provided | Not provided | Not provided | Not provided | Not provided |
| Conclusions | Provided | Not provided | Not provided | Not provided | Not provided |

## 3.3 Tools for inquiry in the lab

Previous research has shown the importance of *tools* for students reasoning and argumentation in science: A globe can serve as "an efficient prosthetic device for thinking […] that embodies and represents a particular conception of the earth" (Schoultz et al., 2001, pp. 103, 117), two pencils can support students in arguing for Newton's third law of motion (Tang, 2022) and two bodies in a rotating dance can support arguments about binary star dynamics (Euler et al., 2019).

Tools that support inquiry can involve anything from the lab equipment or technology we use to gather and process information (e.g. Bernhard, 2010; Sokoloff et al., 2007; Volkwyn, Airey, Gregorcic, Heijkensköld, & Linder, 2017) to the gestures, images and talk (e.g. Andersson & Enghag, 2017; Euler et al., 2019; Gregorcic et al., 2017) we use to communicate and process information (sometimes referred to as signs but here they are also included as tools).

In this part of the thesis I will elaborate on aspects from previous research that involves tools that can be used in lab learning environments and that are important for my research.

### 3.3.1 Lab equipment as tools in lab education

The lab equipment that we use in the laboratory for investigations are essential for inquiry in labs. Their role is often neglected, but our experiences in the lab are often informed through the equipment we use (Bernhard, 2018). Based on previous research (e.g. Lelas, 1993), Bernhard (2018) suggests that this neglects may be due to a view of lab activities as providing direct experiences rather than experiences mediated by the tools we use or due to the view that lab tools have little cognitive value. However, we know that lab tools allow us to experience things that we might not be able to experience with our own senses, i.e. with lab tools we can access and attend to phenomena that we might never have discovered without the tools (Hacking, 1983).

Tang (2022) has argued that the tools and objects we use in science are indispensable when it comes to the formulation of scientific arguments. Previous research (Jordan et al., 2011) has also suggested that it can be important to consider <u>when</u> lab tools are introduced during a lab as it can affect the way students reason.

There have been several other suggestions of how to describe and categorize lab equipment based on what they do, i.e. characterizations of lab tools, and I will present some of these characterizations below.

Volkwyn et al. (2019) describe three types of physics devices based on their function:

1) Intensify: A physics device can intensify a signal from the environment to make it detectable for our senses. The telescope is provide as an example of tool with this function.

2) Filter: This function involves separating relevant information from irrelevant information when gathering information from the environment. Polaroid sunglasses are provided as an example of a tool with this function.

3) Transduct: In social semiotics and multimodality, transduction (Bezemer & Kress, 2008) involves moving meaning across semiotic systems[15], for example from text to speech. Lab tools that have this function are examples that can provide us with information that is otherwise not available to our senses (e.g. Bernhard, 2018; Hacking, 1983a; Kyza et al., 2009). An example of a tool with such a function, i.e. that allows us to expand our observations, is the IR camera (e.g. R. Samuelsson, 2020; Vollmer, Möllmann, Pinno, & Karstädt, 2001).

Volkwyn et al. (2019) add that most tools in physics involve a combination of the functions.

A device can also act as a filter for irrelevant aspects in the environment, such as 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 et al. (2017), who show that IR cameras can direct the attention of learners to the task at hand.

Bernhard (2018) describes how lab tools can transform experiences of the world: Amplification of aspects, i.e. to make something in the world perceiveable or more available for our senses, and reduction, i.e. some tools decreases the scope of observation, for example the telescope.

As mentioned earlier in this chapter, 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 can differ from technology to technology. Thus, it is important in research to also consider and study the learning potential, or *pedagogical affordances* (Airey, 2015), of a tool by analyzing how it is used during a learning process, as "you learn to see through a microscope by doing, not just by looking" (Hacking, 1983, p. 189).

In social semiotics, it is also common to talk about signs and signmaking when studying the tools we use to make meaning with (e.g. Jewitt et al., 2016; van Leeuwen, 2005). Based on the perspectives of multimodality and social

[15] Originally referred to as modes.

semiotics (e.g. Airey & Linder, 2017; Jewitt et al., 2016), Volkwyn et al. (2019) describe how, in general, the meaning of a sign is *flexible* as individuals make and interpret it. 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 and 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 that are brought into the development of it. 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.

Certain combinations of *semiotic resources*, for example touch, speech and visualization, improve learning in particular cases (Clark & Jorde, 2004), but not in others (Schönborn et al., 2014). A failure of improving learning may be due to students 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* that are necessary to understand the task at hand. For example, in the study of Schönborn, Haglund & Xie (2014), the researchers found that students could not reconcile their observations with an IR camera with their prior knowledge and that they tended to use IR cameras as a thermometer. Viewing the situation through a social semiotic lens, the students were not fluent with the *semiotic resources* of the technology as they did not take advantage of the spatial affordance of thermal imagery. It could also be related to the tools themselves in terms of the *affordances* (low pedagogical affordance versus a high pedagogical affordance): 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 aspects of the representation not directly visible, Fredlund et al. (2014) showed how the affordance of the diagram can be shifted from disciplinary towards pedagogical affordance. The shift adds semiotic resources that might be considered extraneous for someone with more experience of the discipline but supporting for a learner. It has, however, also been suggested that it should be possible for a semiotic resource in physics to have both disciplinary and pedagogical affordance (e.g. Airey & Eriksson, 2019; Haglund et al., 2016).

### 3.3.2 The case of infrared (IR) cameras

It has been argued (Hmelo-Silver et al., 2007) that *scaffolding*[16], by for example enhancing the inquiry through technology (Hmelo-Silver, 2006), is important for inquiry-based learning environments. Kyza et al. (2009) described five types of such tools or technologies: Scientific visualization tools, databases, data collection and analysis tools, computer-based simulations and modeling tools. An example of a tool for inquiry that fits two of the categories, scientific visualization and data collection, is the IR camera.

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* but it was still not accessible to the naked eye. Infrared (IR) cameras have made the invisible visible.

All objects above a temperature of 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 that is transparent in IR, for example germanium, and is thus able to detect direct emission of thermal radiation. However, there are factors that can lead to incorrect measurements (for example what type of surface the IR camera is aimed at). Surrounding objects or surfaces should therefore be considered when using IR cameras for quantitative measurement.

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, $\epsilon$, of a body as a blackbody is an idealization (Vollmer et al., 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 camera observations, is 0.95 (close to the value of for example water, wood, silicon carbide, plastics and many paints). The IR camera gives the incorrect readings of "shiny" surfaces, if one chooses 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 crosshair points at. Other points in the image on the display of the IR cameras are given from a chosen color scheme. The chosen color scheme represents the range of temperatures of the points in the view of the IR cameras (see Figure 5).

[16] In this case, scaffolding refers to a kind of support that "(a) enables students to accomplish tasks they could not otherwise do and (b) facilitates learning to succeed even without the support" (Hmelo-Silver, 2006, p. 150).

IR cameras have been used in many areas of research and development, for example in the development of toys that monitor 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). A more extensive explanation of the technology can be found in Vollmer and Möllmann (2010) in which they outline the theory and applications of IR cameras.

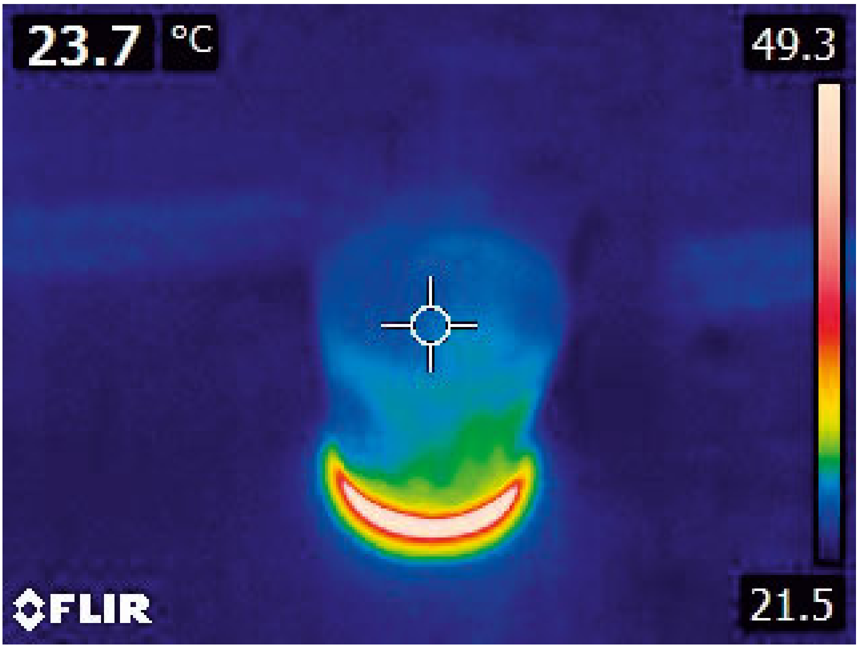


*Figure 5. Thermal image of an exothermic reaction in a plastic cup, generated by an IR camera. The value in the upper left corner indicates the temperature of the point at which the crosshair is directed. The range to the right gives the maximum and minimum temperatures of the image in addition to an indication of what temperature range the colors translate into.*

The topic of how IR cameras can be used in teaching has been investigated by several researchers for the last two decades. Two strands of papers can be found on the topic: *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.

Vollmer et al. (2001) proposed ways of integrating IR cameras in physics education to teach topics such as mechanics, optics and thermal physics. This was followed by other papers that give more suggestions on how to implement the technology in education (e.g. Möllmann & Vollmer, 2007) and by an empirical study (Atkins et al., 2009) in which visitors at a science museum were invited to investigate insulating properties of clothes 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 framed the activity as a lesson and that, by using the IR cameras, they gained a focus for 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 that involve IR cameras. This includes 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 a fire extinguisher 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).

### 3.3.3 Publication I: A review of educational use of thermal cameras

Publication I of the dissertation is titled *Research on educational use of thermal cameras in science: A review* and is published as a chapter in *Thermal Cameras in Science Education.*

The publication is based on the literature review from my licentiate thesis and thus build on the previous section on IR cameras. It was therefore decided that the publication should be described here rather than in chapter 6.

Although not a very big field of research  (16 empirical publications before 2020), research on the educational use of IR cameras has mainly focused on physics education or broader science education and there are two frameworks that have dominated the research: The resources framework and social semiotics/multimodality.

The research on IR cameras from a user, or social semiotics, perspective has focused on the affordances of IR cameras and how they allow students to explore ideas in inquiry activities. For example Dolo et al. (2018) showed that by using IR cameras, students can integrate what their sense of touch in relation to thermal phenomena with what they see with the added technology. This is a sign of the high pedagogica affordance of the IR cameras. In addition, the use of IR camera can allow students to engage in true dialogue (Lemke, 1990), in which they pose their own questions and collaborate. Additionally, the affordances of IR cameras can be described in terms of the affordances of semiotic resources and semiotic systems. Different aspects (semiotic resources and systems) of the IR cameras have different affordances: the numbers afford measurement, the form affords spatial mobility and the color red affords attention to thermal aspects.

The research on IR cameras from a reasoning, or resources framework, perspective has focused on relating the use of IR cameras to two constructs from the framework: resources and framing. It has been suggested that it is important that students have resources that they can activate when they reason about something they investigate with IR cameras, otherwise they can become frustrated (e.g. Schönborn et al., 2014). The resources can be either or both knowledge from informal or more formal educational settings. It has been shown that everyday experiences can be important for younger students (Jeppsson et al., 2017) in reasoning with the IR cameras but also that if students do not have the right resources in reasoning about what they investigate with IR cameras they can get frustrated (Schönborn et al., 2014).

Other studies have focused on how the use of IR cameras relates to framing: Haglund et al. (2015) studied upper secondary school students use of IR cameras in the investigation of thermal phenomena. They found that students tend to have a similar conceptual framing of the phenomena but that they also tend to epistemologically frame the activities in different ways (the example given is one student who wants to follow instructions and another student who wants to explore more freely). In addition the review also includes studies that are included in this thesis, with a focus on students' framing.

The review emphasizes the following aspects in students' use of IR cameras:

- IR cameras allow for instant inquiry – students can use IR cameras to immediately and spontaneously test ideas and explanation.

- Students using IR cameras tend to conceptually frame activities in similar ways, for example using a macroscopic perspective.

- Students can epistemologically frame activities in different ways when using IR cameras.

- IR cameras can be used in generating cognitive conflicts.

- Students using IR cameras need some type of model of heat transfer in order to use them in a fruitful way.

- The use of IR cameras can, given sufficient prior knowledge about the phenomena, lead students to engage in collaborative and engaging dialogue.

- The type of talk students engage in when using IR cameras also relate to students' epistemological framing.

- Students' use of metonyms and metaphors related to the colors displayed by the camera relate to how "heat" is conceptualized (static versus dynamic).

- Thermal imaging has also been show to affect individuals' long-term behavior in how they address issues concerning energy in everyday life.

### 3.3.4 Speech and gesture as communicative tools

The term *tools* can be expanded to also include ways of communicating something, such as *gestures* and *spoken language*. *Spoken language* will be referred to as *talk* as that is the term often used in research about spoken language in the classroom (e.g. see Littleton et al., 2005; Mercer, 1995).

Students' talk is central for collaboration (Mercer, 2000, 2013) which means that the voice, or speech, is a central component of our body for collaborative activities. However, there is little research on communication skills in physics labs (Holmes & Smith, 2023) even though verbal communication is an essential part of inquiry labs (Buning et al., 2018). Holmes and Smith (2023) argue that the lack of research specifically on communication in labs is attributed to the fact that communicative skills are general enough not to depend on the particularity of the activity. In contrast, there are results (e.g. Andersson & Enghag, 2017; Lindwall & Lymer, 2008) that suggest that communicative skills can be related to a particular form of instruction, such as labs. Lab tasks involve many other types of tools than text-based problems and as students' experience is shaped by the tools they use (Bernhard, 2018), there will consequently, in particular in an experimental part of a lab, also be particular types of communication.

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". Brookes and Etkina (2015) argue that it is important to create classroom cultures that allows students to discuss physics without the use of technical terms in order for the students to find a common meaning about physical phenomena that they are introduced to. Technical terms are only to be introduced after this. 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.

The importance of talk has also been emphasized in studies on learning thermodynamics, like being explicit with readouts[17] (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 are 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. 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 presented in 2. Conceptual framework.

There is a personal investment in the arguments of disputational talk that can 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 physics education research by Andersson and 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 and 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 (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 can be referred to as semiotic resources (more commonly referred to as representations in PER (Airey & Linder, 2017). Semiotic resources can form a *coordinating hub* (Fredlund et al., 2012; Volkwyn et al., 2017), a hub in a learning sequence around which meaning can be negotiated between students. For example, Volkwyn et al.

[17] Readouts refer to one's interpretation of sensory input (e.g. Redish, 2004).

(2019) found that students attempting to find the direction of Earth's magnetic field with an 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 is 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.

## 3.4 Thermodynamics and meaning making

The learning environment and the tools are not enough for students to be active and systematic in inquiry-based lab activity. The students' previous experiences, skills and abilities, i.e. more fundamentally their resources, play an important role in how an inquiry-based lab activity will be carried out.

### 3.4.1 Contexts and meaning making

Duit (1981, 1984) shows that the *cultural context* can 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.

As shown by Dreyfus et al. (2014) cultural contexts are also influential in students' reasoning when they move between disciplines: it is possible for student to hold multiple seemingly contradictory ideas as they depend on the disciplinary context. For example, for some students *ATP hydrolysis* can be, from a physics perspective, thought of as requiring energy to break bonds and then, when new bonds are formed, as releasing energy but just as releasing energy from a biology perspective. The students can apply the appropriate perspective in the corresponding context.

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 as the sensations of warm and cold also are related to the body, learners might associate thermal phenomena and "cold" with air (Erickson, 1979; Lewis & Linn, 2003). However, as suggested by Wittmann et al. (2019), "air" might also inhibit students' analysis of energy transfer and transformation as it is not thought of as something energy can flow into.

Following the general ideas of the resources framework (Hammer, 2000; Redish, 2004) and Knowledge-in-Pieces (diSessa, 1993), 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 might 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 changes after introductory physics, e.g. 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 after an introductory physics course. The authors warn of the consequence the change in experience can have on the students future learning and understanding in physics: The changed view of *coherence* can 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 off the ground, sounds reasonable or not. However, Scherr and Hammer (2009) propose that the context of the study (answering a survey) of Redish et al. (1998) might 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 they encounter physical phenomena, e.g. students' answers in a survey do not necessarily reflect how the students reason about physical phenomena.

Wittmann et al. (2019) studied middle school students that worked 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 swinging pendulum. 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.

Students' conceptual problems can also be a reflection of their teachers difficulties with a topic such as distinguishing heat from temperature. Frederik et al. (1999) showed that pre-service teachers are aware of some of their difficulties with understanding heat and temperature and that they expect their future students to have the same problems. It is therefore of outmost importance that teachers at all education levels "teach what they preach": Based on the vision of NGSS in which students practice the scientific practice, Robertson et al. (2019) argue that physicists that teach physics teachers need to take their students' ideas seriously and give them the tools to test those ideas through the scientific practice if they are to do the same for their future students in physics. By accepting the initial ideas as starting points, the authors 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 can be used to check for coherence.

The instructor moves proposed by Robertson et al. (2019) are framed by a resources framework but are not that different from the suggested interventions proposed by research framed by conceptual change, for example teaching maneuvers proposed by Erickson (1979) in teaching about heat and temperature: The "clarification maneuver" in which students are to test their ideas against each other or the "experiential maneuver" in which students are to test their ideas with experiments.

### 3.4.2 Resources and meaning making

Productive resources in the literature[18] include *exemplars*[19] or *prototypes* of everyday experiences (Robertson et al., 2019), such as pouring soup into 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 (diSessa, 2014); or teaching sequences leveraging some of these productive resources in teaching about energy and temperature (Mäntylä & Koponen, 2007; Tobin et al., 2019).

More recently, studies have focused on students' productive resources for reasoning about various physics topics (Goodhew et al., 2018; Robertson et al., 2021). Three types of *conceptual resources* can be discerned in the literature: Resources related to formal physics knowledge, resources related to everyday knowledge and resources that can distract, inhibit or conflict with other resources.

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[18] These studies do not use the terms productive or resources. This is my interpretation.

[19] The resources are not referred to as exemplars or prototypes by Robertson et al. (2019). This is my own terminology that I have applied to relate the paper to the wider research on resources.

It is possible to discern the nature of some of the productive resources of the first type (formal physics) in the previous research: for example that thermal equilibrium seems to support the distinction of heat and temperature (Carlton, 2000; Duit & Kesidou, 1988; Thomaz et al., 1995). For example, a learner might not be able to distinguish between heat and temperature by learning the concepts separately. However, through the concept of thermal equilibrium they will have a relationship between the heat and temperature concepts which leverages the distinction of the two concepts: 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 between the hand and the objects, not a difference in temperature between the objects.

Sabo et al. (2016) identified prevalent conceptual resources that university students in the US use across contexts when they reason about energy: forms of energy were associated with indicators (e.g. kinetic energy associated with motion), changes in energy with indicators of change, energy was related to forces and work, and ideas were used in line with the second law of thermodynamics. In particular, two of these resources are of interest for my research: the indicators resource and the resource related to the second law of thermodynamics. The "form of energy with indicators", or "changes in energy with indicators of change", resource involves students responses where a physical indicator, like motion or change in temperature, was used to justify arguments that involved the presence or change in energy for a system. The "second law of thermodynamics" resource mainly took two different forms in the students reasoning: "energy loss, degradation, and spreading" and "flow of thermal energy from hot to cold objects" (Sabo et al., 2016, p. 16). A large part of the work on students' resources that explicitly takes a resources approach to their studies (Harrer et al., 2013; Robertson et al., 2021) can be found in this first type (although one study can also involve an identification of resources of the other types).

The second type of resources (everyday) includes 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) or p-prims formed from everyday situations (diSessa, 1993). There is not much research about how students use exemplar or exemplar-like resources yet as they have mostly been associated to students' prior, incorrect, understandings.

The third type of resources are resources that inhibit, are in conflict with or distract other resources that could have been productive for meaning making (in terms of the learning target set by the teacher). This does not mean that the resource in itself is inherently wrong, but that the activation in a particular context can lead to a challenge for students (e.g. disagreements, distractions or cognitive conflicts), that makes it difficult for students to progress with their activity. There is as yet no term for this type of resource but a common way to refer to them is as *barriers*[20] (Loverude et al., 2002), which is the term I have chosen to use for the next section of the literature review that focuses on these constructs and how they inhibit learning and the understanding of thermodynamics. Barriers are context-dependent and examples of barriers when learning about heat include the *substance metaphor*: The *substance metaphor* can be a *productive resource* in understanding energy conservation (Scherr, Close, Close, et al., 2012) but can act as a *barrier* in understanding heat as a process (as heat as a substance leads one to believe that heat is a state function (Brookes et al., 2005). Here, a metaphor relating to currency can be a more productive resource (which is productive for explaining both energy conservation and degradation (Daane et al., 2014)).

Multiple studies in PER deal with 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 and Driver (1985), they interview students about conduction of heat and notice that an idea that influences the students' reasoning is 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 if it were heated from the side and argues that it is what they were told in science class (see p. 178 in Clough & Driver, 1985). This is a kind of *heuristic* (Tversky & Kahneman, 1974) that the authors, Clough and Driver, 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 that inhibits other resources that might have been productive for the reasoning process.

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). They, for example, tend to view temperature as the unit for heat (Greenbowe & Meltzer, 2003) or equate heat with temperature (Erickson, 1979). Additionally, students can use the sense of touch as a thermometer, which leads to the conclusion that different objects at thermal equilibrium have different temperatures, see for example Schönborn et al. (2014). This seems to indicate that the sense

[20] Like resources, barriers are 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 resource that is associated to this object. This association may differ between individuals or groups but the barrier's 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".

of touch is a barrier in distinguishing temperature and heat, but this is not always the case as, for example, Carlton (2000) shows that it can be a productive resource for heat transfer if it is used as a starting point for teaching about heat.

Frederik et al. (1999) suggest that some of the difficulties with understanding the relation between heat and temperature might be because of the association between heat transfer and temperature increase (e.g. *"heat transfer leads to temperature increase"* as a barrier[21]) 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, however, is 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, see Hewitt, 2015, p. 353).

Rozier and Viennot (1990) show how students tend to reduce the complexity of a problem in thermodynamics involving the ideal gas law and that this stems from a variety of different reasoning procedures ranging from reduction of variables to what they refear to as linear causal reasoning (e.g. A leads to B leads C). Loverude et al. (2002) and Leinonen (2013) show how the *ideal gas law* can act as a barrier in using the first law of thermodynamics in problems involving adiabatic processes. The ideal gas law has also been shown to act as a barrier in understanding vapour pressure (Azizoglu et al., 2006) and similarly using the *substance metaphor* in learning about heat as a process (e.g. Brookes et al., 2005; Brookes & Etkina, 2015) acts as a barrier.

## 3.5 Identification of gaps in previous research

The physics topics of my studies include phase transitions, latent heat and calorimetry. However, there are few papers in physics education research that deal with phase transition (e.g. Hughes & Schouten, 2023; Schouten et al., 2012), latent heat (Carlton, 2000; Mak & Chun, 2000) or calorimetry (e.g. Greenbowe & Meltzer, 2003) and these are mainly papers on instructional design, rather than empirical research. However, these concepts all relate to some important difficulties that earlier 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 formation or breaking of chemical bonds (e.g. Dreyfus, Sawtelle, et al., 2014). In particular, Greenbowe and Meltzer (2003, p. 796) suggest that calorimetry "offers the best opportunity to clarify the distinction between heat and temperature".

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[21] My own interpretation.

Publications on IR cameras most often focus on proposed activities using IR cameras, and very few papers theorize about IR cameras as a tool in inquiry-based labs (e.g. Haglund et al., 2015; Larsson et al., 2019). I would argue that my research contributes to this part of PER.

Additionally, the research explicitly employing the resources framework in order to study students' conceptual resources mostly focuses on problem-solving  and there is a lack of research done on students' resources in lab education. Also, most research on metacognition, which relates to what I refer to as epistemological resources, has been carried out outside of physics lab contexts and is focused on problem-solving (Holmes & Smith, 2023).

# 4. Research questions

As presented in chapter 1, the purpose of the research is to identify what resources (conceptual, epistemological and semiotic resources) support two types of student activity in inquiry-based labs, both active and systematic engagement, and ways that students can address challenges that they encounter during their activity.

The conceptual framework and literature review, provides a background to these types of resources, with a focus on thermal phenomena, involving phase transitions and heat transfer, within inquiry-based labs based on different degrees of openness.

Against this background, the thesis is guided by the following research questions:

**RQ1:** What resources can support students' active engagement during labs of different degrees of openness?

**RQ2:** What resources can support students' systematic engagement during labs of different degrees of openness?

**RQ3:** How can potential challenges in labs of different degrees of openness be addressed?

# 5. Methodology

I will here give an overview of the overall methodological approach of the thesis and point out methodological similarities and differences between the individual studies. The specific methods for the studies can be found in the individual publications.

## 5.1 Naturalistic inquiry

Education research 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 number of molecules rather than a single molecule, it makes more sense for some education research to be conducted with *quantitative methods* (e.g. comparing students' performance within two different curricula for a country through statistical analysis), thus generating results for a collection of "molecules", and other research to be conducted with *qualitative methods* (e.g. through interviews and discourse analysis investigate how a specific group of students experience a specific topic within physics), generating results about interaction for one or within 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 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 that the same researcher analyzes the two cases).

The two approaches should be thought of as complementing and informing each other. That said, I have chosen to apply *interpretative qualitative methods* in the studies included in this thesis, as that approach better serves to answer my research questions (involving the process of students' meaning making). In terms of data collection, qualitative methods (e.g. interviews) are usually more time-consuming than quantitative methods, which means that the number of participants that generated the data is rather limited.[22] However, returning to the analogy of particles, more time might be spent on each "molecule" of the data, which, although making the findings more *trustworthy* (Guba & Lincoln, 1982) on a small scale level, might be difficult to generalize

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

to other groups, such as education in the country in general or for learners in general.

Guba and Lincoln (1982) question the reliance on the traditional rationalistic paradigm in the study of human behavior.

A learning situation where the data are generated by humans, that have their own will and behavior, might depend on thousands of known and unknown variables. Another type of approach is needed in which the behavior or action of a specific group of learners in a set environment is seen as more or less plausible rather than fixed or probabilistic could be fruitful (Guba & Lincoln, 1982). Guba and Lincoln (1982) offer this through what they call the *naturalistic paradigm.* Their paradigm involves a set of five axioms that are 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 research is to develop *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, depending on how similar situations are in terms of contexts and temporal aspects, there can be some transferability from a working hypothesis for one case to another.

4) Many factors shape an action, and we as researchers 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 the *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 postures that describe common decisions for a researcher of naturalistic inquiry, for example, choosing the settings that are natural to the participants and studies events (e.g. studies in the classroom rather than in the psychology lab).

Initially, my studies have been quite open regarding what they aim to investigate: In II, engineering students made unexpected observations, which formed the basis for the paper. Initially, we recorded the engineering students during their course lab in a very open-ended way to explore their practice and reasoning. Similarly, engineering students with access to IR cameras (III) were free to do whatever they wanted with them, which meant that we did not know what to expect before gathering the data. Other studies, like IV and V (and the modified labs in II and III), had a stronger basis in the design of the learning environment. Nevertheless, most of the studies (with the potential exception of V) have been conducted within or in connection with students' regular courses to keep the contexts more authentic.

The axioms of the paradigm that inform my methods, or the assumptions that act as a foundation for my research, thus aim at embracing the messy or complex real-world conditions. What I mean by 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 that is similar to what is used in regular classes and in a setting that is typical for teaching that topic. As an example, if one is to study how the intervention of IR cameras affects the learning of 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 a milieu similar to 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 regularly. The main limitation of research carried out in naturalistic settings is that it is time-consuming and difficult to keep some sort of experimental control of the event (K. Dunbar & Blanchette, 2001).

Dunbar and Blanchette (2001) propose a way of combining research that takes place within the authentic setting (*in vivo*) with research in psychology labs (*in vitro*): In vivo research can be used to generate hypotheses that can be tested in a more controlled, in vitro, environment. My publications are of different degrees of authenticity when it comes to the setting: Starting with II as the purest form of in vivo research and moving on towards in vitro aspects in the order III, IV, and V. II emerged through data that were generated within a naturalistic setting and the naturalistic instruction (it emerged from the lab instructions of the course that the students' were enrolled in). Similar to II, the study of III was mostly done in a course setting, but we provided some students with IR cameras as part of the course lab, so the intervention was slightly larger. The setting in IV was also naturalistic (conducted in one of the classrooms in which the students had their course lecture). However, my co-authors and I designed the instructions, or the teaching sequence, partly based on the results from II, thus adding some research-specific in vitro aspects of the design (but still keeping the overall naturalistic nature of the study). The same can be said for V, which involved an inquiry-based activity, similar to activities that some of the students had worked with within their course but not as part of an actual course.

In this way, II and III could be considered more authentic than the others. However, there are other ways of looking at the contexts of the studies: For example, V involves an instructional approach, the Investigative Science Learning Environment (ISLE), which "mirror[s] the processes and procedures that practicing physicists use when developing and applying physics knowledge" (Etkina et al., 2021, p. 1). In other words, although the activity is not carried out within a formal course moment, the instructional approach mimics an "authentic" approach to experimental physics.

## 5.2 Probing methods

The empirical studies of this thesis (II-V) use Prediction-Observation-Explanation (POE) and Investigative Science Learning Environment (ISLE) to structure students' investigations and interviews with the participants.

### 5.2.1 Prediction-Observation-Explanation (POE)

*Prediction-Observation-Explanation (POE)* is a method introduced by White and 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 proposed to be used as a probing method of students' understanding.

POE involves three stages: Give information about a topic and initial conditions for a phenomenon. Students are to *predict* how the phenomenon will unfold and the outcome of the phenomenon, followed by students' *observation*. Finally, students are asked to *explain* their observations, 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, will reach the ground first if they are 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.

As the resources framework frames my studies, POE is used to probe for *productive resources* in students' reasoning process about phenomena. Students are expected to learn what kind of knowledge is useful in a particular situation rather than forgetting their previous ideas.

There are variants that combine the parts of POE into other sequences, like PDEODE (Savander-Ranne & Kolari, 2003) where D stands for Discuss. I have, in a similar way, adjusted POE in my studies (when it is used as a probing method) by building new chains of the parts of P, O, and E: The phenomenon in II emerged out of an observation by the students, which they were asked to explain and then predict the impact it would have on the experiment. By providing them with IR cameras, they were allowed to observe the phenomenon again, but in a new way through the added thermal image, and add to their explanation.

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 of openness in formulating questions for 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 observation is referred to as *reactive observation* (Angrosino, 2012), an approach in which the participants know the researcher's intentions and role, and interventions are made by the researcher during the observation, for example, by posing open-ended questions.

### 5.2.2 Investigative Science Learning Environment (ISLE)

The *Investigative Science Learning Environment (ISLE*) could be described as an inquiry-based instructional framework that gives students a lot of openness in terms of what they can do during an activity. It provides a structure (make observations, propose hypotheses, design testing experiments, make predictions, and carry out experiments) that students can use to organize their practice through. The basic idea is that students engage in scientific practice through cycles of investigation of a presented phenomenon (Etkina et al., 2021): Initially, students are presented with an observational experiment where they are to describe, in simple words, what they are observing. They are then to come up with potential explanations of the observation, i.e., hypotheses, design testing experiments for those explanations, predict the outcome of the experiments, and carry out the testing experiments to see if they match the predicted outcomes. Additional testing experiments will be designed and carried out if the outcomes match the predictions. Students can carry out additional observational experiments, propose new explanations or check the assumptions of the predictions if the predictions do not match the outcomes.

The philosophy of ISLE has two goals (Etkina et al., 2021) when it comes to learning and teaching:

1) To support students in developing practices similar to those of physicists.

2) To support students' motivation and confidence, which includes both students' emotional and intellectual development.

The intention is for students to feel that they can freely propose ideas and design experiments to test those ideas without putting their personal integrity at stake. As a result of this intention, testable explanations are sometimes referred to as “crazy ideas”. It is likely to make students feel more comfortable in testing ideas that are not necessarily “right” or having students describe their initial observation with simple language so that all students initially have the same conditions.

In contrast to the body of research on lab education related to lab skills (e.g. Smith et al., 2020) that often focuses on lab activities where students work with quantitative data, ISLE allows for lab activities where students can spend more time with qualitative data, e.g. where students study and describe patterns without the support of statistical analysis. This further levels the playing field for the students in that even those without strong prior knowledge of mathematics can participate in the investigation (Etkina et al., 2021).

The philosophy shares some of the motivation of the resources framework, which was also developed to respond to previous ideas that pointed out students’ problems rather than identifying the usefulness of students’ current ideas. For example, Robertson et al. (2019) argue that when physicists teach physics teachers, they should strive to take their students’ ideas seriously as physicists would and then help them to find ways to test 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.

Additionally, in line with recent calls (Smith & Holmes, 2021; Walsh et al., 2022) for more epistemology-centered (rather than conceptually centered) labs, the instructional framework of ISLE emphasizes lab skills. However, conceptual aspects are not ignored, as typical activities center around physics topics and phenomena.

## 5.3 Data collection

Three types of participants are included in the data of the empirical publications (II-V): Teacher students (IV and V), engineering students (II and III), and instructors (Ph.D. students in physical chemistry). Some of the engineering students specialize in chemistry, and some in physics.

Research in PER has explored all of these types of cohorts in relation to physics: chemistry and physics (e.g. Dreyfus, Gouvea, et al., 2014; Geller et al., 2013; Greenbowe & Meltzer, 2003), teacher education and physics (Etkina et al., 2017; J. Larsson, 2019; Wittmann et al., 2017), and instructors and physics (e.g. Robertson et al., 2019) from a PER perspective. My aim in choosing these groups, however, is not mainly to contribute to these bodies of research but rather to have a diversity in students’ backgrounds and experiences of physics.

An overview of the data is presented in Table 4. I refer the reader to each individual publication for additional details on the data.

The language used in all data collection was *Swedish*, which was translated to English by me before publication (selected excerpts of dialogue were translated for publication), and after crosschecking the translation with other authors of the papers. All authors but one (Charles Xie in IV) are fluent Swedish speakers.

All sets of data were collected through video recording. The participants' interaction was transcribed using *multimodal conversation analysis* or *thematic analysis* as a basis for the transcription procedure. I observed the students in the instructed lab from the start (after they had been informed and agreed to participatr in the study). I varied between observation and note-taking, and video recording and probing the students about their practice (when something was unclear). I tried to remain at a certain distance while observing, not to interfere too much with their naturalistic practice.

There is something to be said about that balance between being able to probe for students' reasoning and students' awareness of being a part of research: The presence of the researcher could potentially lead to the students framing the situation differently than they would have if they had not noticed my presence, thus modifying their talk and reasoning by what they expect is probed for in the research they participate in (sometimes referred to as the *Observer's paradox* (Labov, 1972)). My goal in being present in the room was mainly to ask students clarifying questions and thus act as a reactive observer (Angrosino, 2012).

*Table 4. Overview of the contexts of the data in publication II-V.*

| | *Publication* | | | |
|---|---|---|---|---|
| | II | III | IV | V |
| *Cohort* | One pair of engineering students<br>One pair of instructors | Four pairs of engineering students | Group of five primary school science teacher students | Three pairs of high school physics teacher students<br>Three pairs of engineering students |
| *Instructional approach* | POE-based inquiry | POE-based inquiry | POE-based inquiry | ISLE-based inquiry |
| *Thermal phenomenon* | Salt (NaOH) exothermically reacting with water | Salts (NaOH and $NaNO_3$) reacting exothermically and endothermically with water | Evaporation and condensation and changes in temperatures (e.g. evaporative cooling) | Melting (freezing point depression) and decrease in temperature |
| *IR cameras* | Not provided initially. Available in the activity (the modified lab) following the course lab. Instructed use. | Provided to two of the pairs in the course lab. Provided to all pairs in subsequent activity (the modified lab). Free use during course lab. Instructed use during the modified lab. | Provided for each stage of the teaching sequence. Embedded in the design. | Available as one of several instruments when getting access to the lab material (after having proposed testing experiments) |
| *In vivo/in vitro* | Within course lab | Within course lab | Following regular class | Outside of course |

## 5.4 Analysis

Researchers need 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. In my case, the context involves inquiry-based lab activities with different degrees of openness.

### 5.4.1 Thought, talk, and action

There are roughly two categories of what can be directly observed in video data of students working in a learning activity: their actions (e.g. how they move their body, what they interact with, gaze and gestures) and their talk or communication in terms of speech. The latter could be included in the former but is often much more prominent in the data and is the primary mode of communication that has been traditionally studied with conversation analysis (Jewitt et al., 2016). This method will be discussed in the next section. A third category that is often indirectly inferred is that of students' thoughts. Lemke (1990) questions the possibility of ascribing mental models to people beyond what is directly observable through speech and action. However, I argue that it is possible and important for teachers and educational researchers to infer something about students' thoughts from their actions and communication. Additionally, cognitive processes are more often treated as being extended beyond the individual's mind and brain, in terms of an extended mind (Clark & Chalmers, 1998) or interthinking (Mercer & Littleton, 2007). Students' thought processes can either be inferred from what students say or how students act, but a more straightforward way of studying thought is through students' explicit talk about how they think (e.g. "But I remember…", "I think about it in this way…" or "This makes me think of…"). It might be rarer for students explicitly talk about their thought but arguably more convincing than talk that explicitly does not refer to lines of thought.

Mercer and Wegerif (2001) discuss two approaches to research on talk: experimental studies that involve coding, which results in quantitative data, and observational studies that use qualitative methods for interpretation, mainly focusing on the processes rather than the outcome. The critique against the former type is that it often "hides" the original data behind codes. I have used as many transcripts as possible in my publications, in addition to coding, in order to somewhat deal with this problem. As Mercer and Wegerif write, there are still problems with this type of presentation of data as the generalizability can suffer.

I have transcribed all my video data manually (without any help from software) in a spreadsheet. Manually transcribing video data takes much more time than using a software like NVivo for processing the data. However, it has allowed me to get more familiar with my data and think about the analysis while I am processing my data into transcripts.

### 5.4.2 Multimodal conversation analysis

Early *conversation analysis* research 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 research that applies 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. In other words, fieldwork is preferred in collecting the data rather than gathering the data in a research laboratory where participants are prompted to talk (Jewitt et al., 2016). This idea of considering the setting in which the research is carried out aligns with the idea about framing and contextual cues that affect how we learn and reason about a phenomenon or problem. Suppose we keep the setting as close to students' regular teaching settings as possible. In that case, the result can 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 value in adding a layer of analysis of multimodal aspects such as gestures to data analysis of video data. For example, Euler et al. (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 acts 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 are then collected by video recording). Pioneering research using *multimodal conversation analysis* includes much of the work of Goodwin: Goodwin (1979) included gaze as one of the main modes for analysis when he investigated how gaze shifts 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 practitioners' speech when they work with an excavation. Both papers mentioned include multimodal conversation analysis as a method for processing and analyzing the data. Multimodal is used in the sense that they include other ways of communicating than just speech that are deemed 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 my publications:

1) The focus of the analysis is video clips. The analysis should stay close to the selected clip. 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 that are important for each study's aim. 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 manual transcription of the chosen clips and new data sessions where my co-authors and I have discussed the transcription when watching the clips. Additional iterations have consisted of new transcriptions and discussions among the authors on potential themes or patterns found in the data. The final transcriptions have been translated to publish in international journals.

In addition to these two principles, Mercer's (1995) *typology of talks* has been used to analyze the participants' speech patterns. The original idea of Mercer was not to use the typology as a way of categorizing all observed speech but rather to support an understanding of how learners use talk to think together. I have used the characteristics (or what Mercer refers 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 contains *disagreement* and *individualized decision-making* would be interpreted as *disputational talk*, with *repetitions* and *confirmations* as *cumulative talk*, etc.

The different studies (II-V) have all involved multimodal analysis to some degree. Although some of the studies (II, IV, and V) also have included multimodal transcripts at some stage during the work with the data, one (II) has leaned more heavily into the multimodal analysis (as the study focused on affordances of semiotic resources). Structuring data with multimodal categories takes a lot of time (each mode can require its viewing of the video data), and it is sometimes not possible to write full transcripts of all the different shifts and actions in the data for each mode that might be interesting for the analysis. For most studies, I have mainly relied on transcripts of the participants' speech with potentially important multimodal aspects in brackets regarding the final transcripts. However, I have also watched the recorded videos iteratively to identify important multimodal aspects directly from the video data.

Examples of the transcripts from each study are presented in Appendix B-E.

### 5.4.3 Thematic analysis

I based my analysis for V on ideas from thematic analysis (Braun & Clarke, 2012). This analysis process involved an initial summary of patterns that we noticed in the first viewings of the video data and, after transcribing the data, an inductive approach to coding the transcripts. The codes were in parallel compared to the patterns in the summary and some concepts (e.g an exploratory mindset, metacognitive reflection, and procedural self-regulation) that were found relevant to the study (i.e. a deductive approach). It is rare to take a purely inductive approach as "we always bring something to the data when we analyze it, and we rarely completely ignore the semantic content of the data when we code for a particular theoretical construct" (Braun & Clarke, 2012, pp. 58–59). Some of the similar codes were later combined, and the analysis was discussed within the group of researchers working on the study in iterations. An example of a part of the initial summaries and transcripts is presented in Appendix E. The summaries were used to generate codes that later could be used to build categories or themes for the transcripts (more detail on this in V). They were also used to get an idea of the systematicity of the participating groups of students: The middle and right columns in the first table, in Appendix E, track how well all the stages (e.g. observations, hypotheses, and experiments) of the activity hang together and the extent of the students' work for each stage (e.g. how well the phenomenon initially is described).

### 5.4.4 Structuring the review of research on infrared cameras and education (publication I)

The review of research on infrared cameras was structured by analyzing previous studies on using infrared cameras in science education (see Appendix F). The studies were found by searching (through Google Scholar) for papers with keywords like "infrared cameras", "education" and "science education", in addition to browsing the reference lists of the publications that already were known to me. Each identified publication was, in the table, assigned keywords for what type of publication it was, the theory, and the methodology. Common keywords formed the themes that later were used to structure the writing of the chapter (I).

## 5.5 Establishing quality in research

The context in which naturalistic research is carried out is crucial for the interpretation of research results (see Guba & Lincoln 1982, p. 92). I agree and have kept my studies within the educational context that the students participate in for my work in this thesis.

In their seminal paradigmatic proposal for a constructivist approach for naturalistic inquiry, Guba and Lincoln (1982) argue for establishing trustworthiness as a mechanism for naturalistic inquiry that is equivalent to traditional positivistic ideas of internal and external validity, reliability and objectivity.

Guba and Lincoln's four criteria of trustworthiness are as follows:

1) **Credibility**: Given an account by the 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.

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 carry 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 and Lincoln (1982) to an extent on these criteria, but there are aspects where I would give an alternative control mechanism that fulfills 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 when 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 have been appropriately rigorous and critical as a researcher who was not a part of the original study. Additionally, using multimodal conversation analysis as a method for analyzing and interpreting data, each iteration and data session contribute to ensuring the criteria of consistency (which the *dependability* criteria is a naturalistic form of).

Similary there are alternative ways of viewing aspects such as *transferability* and *generalization*. For my work, one such alternative is offered by Bassey (2001, p. 6) through 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". As in the initial argument, made by Guba and 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 for achieving 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)

Often an attempt to try to replicate a naturalistic study would be impossible: Similar to replicating the pattern in which a set of feathers fall when throwing them outdoors on a windy day. Like Guba and Lincoln (1982), Bassey (2001) argues for the potential of transferability (the "fit" in Bassey's words) between situations that share similarities, and that it is thus necessary for the researcher to provide thick descriptions informing others on the potential of transferability of the results. In my studies confirmability was established as characterized earlier and summarized later.

An aspect important in establishing dependability is the inquirer being the same for all data collections. This limits the way participants get affected, for exampled by what questions to pose to the participants.

When Guba & Lincoln (1982, p. 250) propose their paradigm of naturalistic inquiry, they also add that at the time of writing, "the naturalistic school is only beginning to develop an arsenal of weapons against the charge of non-rigor or untrustworthiness". Although not considered, conversation analysis as a method has ways of dealing with the *trustworthiness of analysis* through the transcription process. This involves iterative data sessions where researchers meet to check on each step of interpretation of the data. In my case this was done by me transcribing all video data and then reviewing both the previous step of data processing and the current one. For example, the video data and the first iteration of transcription, together with my co-authors in a data session. To summarize the measures that I took 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 (IV and V) and chemistry student (II and III), two experiences that give me access to the features salient in the environment for an outsider.

2) **Transferability** – contextual richness in description: By describing the participants, the teaching material, the setting, contextualization of problems and the temporal order (see Table 4) I have established 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: The phenomena central to II and III are all important for the students' regular course work and knowledge about the chemistry lab. All experiments in IV and V relate to everyday situations and are cheap (in terms of the material other than the IR cameras) 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. This 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 are trackable through the stages of processing that they have gone through from the raw data (video recordings) to the published data (transcriptions of clips). For my later publications (III and V), I have kept a record of the initial process, of planning and analysis, by creating a PowerPoint presentation where I present the work chronologically (this has also been used as a way for me as lead author to present the progress to the co-authors).

## 5.6 Ethical consideration

There is a potential dilemma in carrying out naturalistic research and at the same time considering ethical issues as one of the more important ethical considerations when dealing with people 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 decided to make the information about the purpose of my research and the exetent of 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, where participants could be identified, in publications. All participants who wanted to participate had to sign consent forms giving 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 using IR cameras is how to handle thermal images of people generated by the cameras. IR cameras generate a dynamic visualization of the environment by exposing aspects relating to temperature. These images could also be recorded as static images and used for research publications or students' project reports. However, aspects that normally go unnoticed and that can be experienced as embarrassing for some students can be highlighted through the camera, for example warm spots on the body, sweating and even information about medical conditions such as rheumatoid arthritis (Pauk et al., 2019). I have specifically chosen not to record any thermal images of 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 publications regarding what formal rules were followed in considering research ethics, as data for II and III was collected before *The General Data Protection Regulation (GDPR)*. However, the participants in II and III were informed about the reasons for doing the study, their rights of withdrawal from the study at any moment and that their identities would be protected in the publication. Students who wanted to participate signed consent forms (see Appendix A).

The data for IV and V was collected in accordance with GDPR.[23] Students were informed both verbally and through written information about their 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).

[23] The data collection for II also follows the ethics of GDPR but was collected before GDPR was enforced in the European Union.

All data are stored on an external hard drive and only shared among the involved co-authors and other researchers[24] that the participants have agreed to include among the people that 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.

[24] Researchers that in accordance with GDPR all are situated within the EU. This meant that one of the co-authors of one the publications (IV), Charles Xie (situated in the US), did not get to view the raw data, only the processed data (transcripts).

# 6. Publications of the thesis

This part of the thesis provides overviews of the context, analysis of the data, and subsequent discussion of the results in the empirical publications (II-V). The published book chapter (I), that provides a literature review of research on the educational use of IR cameras, is summarized in chapter 3.

## 6.1 Publication II, Hot vision: Affordances of infrared cameras in investigating thermal phenomena

Publication II is published in *Designs for Learning*.

### 6.1.1 Context

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

I participated in the lab as a reactive observer (Angrosino, 2012). 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. On one of those occasions, two students notified me that they had observed something 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 left out in the open. The students noticed that the pellets had turned glossy and wet. After their course lab but in the same lab environment, the students were later introduced to IR cameras to observe and explain the same phenomenon again.

Two Ph.D. students in physical chemistry that acted as instructors in the lab were asked to perform the same task that the students had done to compare the students' use of the cameras and their talk while investigating the phenomenon with instructors who had much more experience with the lab than the students. These two Ph.D. students came from two different research fields of physical chemistry (material and inorganic chemistry). 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 as "novices" and "experts" in relation to each other (the instructors have more experience with the disciplinary content than the engineering students).

Data was collected through video recording and subsequently multimodally transcribed (with categories such as body movement, interaction with artifacts, and gaze).

### 6.1.2 Analysis and discussion

The analysis compares the pre-intervention, sequence 1 (no IR cameras) with the intervention, sequence 2[25] (access to IR cameras) of the students' instructed work, and both interventions of the students and the instructors (sequence 3) in regards to how they interact with the phenomenon and tools, and how they talk in their discussions on the phenomenon and the tool.

While working with their course lab, the students discovered that the sodium hydroxide prepared in a container looked like it was melting or was sticky. This observation led the students to formulate a set of alternative hypotheses or explanations. However, they could not make any tests. They continued with their course lab until they were invited to the intervention and provided with IR cameras to study the phenomenon (deliquescence) they had discovered during the course lab. With the IR cameras, they quickly observed that the salt was red, which led them to conclude that it was warm and that an exothermic dissolution reaction had started, thus supporting one of their previously formulated hypotheses.

The students engaged in *exploratory talk* when they discovered the phenomenon but shifted to cumulative talk when they had access to the IR cameras. Additionally, they became less dynamic in terms of behavioral activity. During the course lab, they lifted the container with the salt to point out their discovery, but with the IR cameras, they shifted to fixed positions. Several points might seem surprising at first, for example, 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 et al., 2015; Haglund, Jeppsson, & Schönborn, 2016) has shown that IR cameras invite *instant inquiry* in which students can come up with questions on the spot and test them with the cameras. Engaging in instant inquiry is described as a type of *epistemological framing* by Haglund et al. (2015) that, as they show, might not depend on the cameras but rather on the individual learners; some students want to stick with the instructions, and others want to explore more freely. The fact that the students, in this case, did not take the opportunity to engage more with instant inquiry could thus be a result of the

[25] The learning environment for this sequence (and sequence 3) will be referred to as the modified lab in analyzing and discussing the overarching themes and patterns of all the publications.

individual students' epistemological framing of the situation (follow the instruction).

The instructors were quick to describe the observation and explain it. They were also quick with manipulating the experiment by moving a container to see the temperature increase on the table due to the exothermic reaction and heat transfer.

After the initial observation, the instructors engaged in exploratory talk, which led to more elaborated explanations that risked ending in a disagreement which the instructors solved by referring to their respective identity as researcher (their specific research fields).

A summary of the analysis is available in Table 5.

*Table 5. Patterns of talk, interaction, body and gaze in the three sequences analysed in II.*

| *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<br><br>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 |

During sequences 2 and 3, the participants had access to the IR cameras. While the students used the IR cameras to support one of their previous explanations quickly, the instructors manipulated the experiment more freely to test their ideas, which suggests an exploratory framing of the situation. In addition, the instructors engaged in cumulative talk when making the initial observation with the IR cameras. They shifted to exploratory talk 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?).

The instructors engaged in exploratory talk, unlike the students for the same activity (sequence 2 and 3). This difference was suggested to be based on the fact that the instructors are much more experienced with the phenomenon than the students. Their experience allows them to engage in exploratory talk and to be more dynamic in their investigation. The instructors manipulated the experiment and varied how they investigated it, especially when gathering and sharing information. By doing this, they varied the involved *semiotic resources* (the *color* image and *numbers* changed when they moved the camera, which is done through the *form* of the camera).

The colors, numbers and form of the IR camera are types 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 6.

*Table 6. 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 (the participants 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)*[26] | *Function* | *Participants* | *Main affordances* |
|---|---|---|---|
| *Colors* | Initiate and frame the reasoning | Students (explicit) Instructors (implicit) | Attention to thermal phenomenon |
| *Numbers* | Support the interpretation of colors | Students (implicit) Instructors (implicit) | Measurement and quantification |
| *Form* | Allow for shifts in interaction with IR cameras and experiment | Instructors (explicit) | Spatial mobility |

[26] Semiotic system is used in Table 6, but I do not claim that the semiotic system itself has the affordances. It is rather the set of semiotic resources of that semiotic system available to the participants in the context that has these affordances (e.g. the semiotic resources of red and blue of the semiotic system of colors). I have chosen to use the term *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 resources (e.g. the range of temperatures displayed could vary between 20-70 $^0$C depending on the investigated phenomenon).

## 6.2 Publication III, Looking for solutions: students' use of infrared cameras in calorimetry labs

Publication III is published in *Chemistry Education Research and Practice.*

### 6.2.1 Context

The study involved four pairs of engineering students in a calorimetry lab that was part of a thermodynamics unit in an introductory chemistry course. Just like in II, the students were supposed to carry out experiments in which salts (sodium hydroxide and sodium nitrate) were added to water, and the resulting change in temperature of the solution could be used in order to calculate the enthalpy change of the solution supported by the Born-Haber cycle. However, in contrast to II, two pairs (IR1 and IR2) of students were given access to IR cameras to use as they liked during their course lab. The pairs were video recorded during the sequences when using the IR cameras (both pairs chose to use the cameras during one of their experimental runs for each salt). The other pairs (T1 and T2) did not have access to IR cameras and had their lab on a different occasion than the IR pairs. These pairs were video recorded during the same sequences that the IR pairs were recorded so that it would be possible to compare how they worked during the experimental runs regarding reasoning, communication, and practice, with or without IR cameras.

After the pairs had finished the course lab, they were all invited (one pair at a time as soon as they were finished with their coursework) to investigate the same phenomena (exothermic and endothermic reactions) in a separate room and with containers adapted for the IR cameras: Transparent plastic cups were used instead of the insulating Styrofoam cups that the students had used during their course lab. Additionally, the salt was added without a magnetic stirrer which meant it was possible, with an IR camera, to see a temperature gradient resulting from the exothermic reaction and thermal convection. This activity after the course lab is referred to as *the modified* lab in the publication (and the sequence from the course lab is referred to as *the course lab*).

Conversation analysis (Jewitt et al., 2016) and thematic analysis formed the base for analyzing the data. The data was analyzed in iterations, which ended up with four categories of students' activity: interaction, communication, and type of content of the students' reasoning, how easy the reasoning was to follow, and how relevant it was for the lab activity (referred to as "quality of content" in the final results). The result was summarized in a table (see Table 7).

### 6.2.2 Analysis and discussion

The full analysis and discussion can be found in the paper. However, I will here describe the points that are important for the thesis and elaborate a bit on what the result of the study tells us in terms of students' engagement within the lab activities in which they participate.

*Table 7. Overview of the results of III (based on Table 1 in III). The quality of students' reasoning was either coherent or incoherent (all reasoning was deemed relevant), the type was either macroscopic or both macroscopic and submicroscopic, the practice continuous or intermittent, and finally, the communication self-initiated or responsive.*

| *Lab* | *Aspect* | *IR1* | *IR2* | *T1* | *T2* |
|---|---|---|---|---|---|
| *Course lab* | Quality of reasoning | Coherent | Coherent | Coherent | Incoher. |
| | Type of content | Macro. | Macro. | Macro. & submicro. | Macro. & submicro. |
| | Practice | Contin. | Contin. | Intermitt. | Intermitt. |
| | Communication | Self-initiated | Self-initiated | Responsive | Responsive |
| *Modified lab* | Quality of reasoning | Coherent | Coherent | Coherent | Incoher. |
| | Type of content | Macro. | Macro. | Macro. | Macro. |
| | Practice | Contin. | Contin. | Contin. | Intermitt. |
| | Communication | Responsive | Responsive | Responsive | Responsive |

From the results (see Table 7), it was possible to conclude that the use of IR cameras led to a macroscopic focus (a *conceptual framing*) in terms of what the students talked about. In contrast, the T pairs talked about the phenomena' submicroscopic and macroscopic aspects. Additionally, the IR pairs initiated their communication mostly on their own (*self-initiated* communication), in contrast to the T pairs that were *responsive* in their communication (i.e. it was more common for them to not discuss anything until they received questions from the lab instructor or researcher).

The IR pairs were also *continuous* in their practice (e.g. they interacted more with the experiment by studying it from different angles). However, when they moved on to the modified lab where all students had access to IR cameras, all students maintained the type of reasoning in terms of how *coherent* and relevant it was for the activity. However, the T pairs shifted in the type of content of their reasoning to focus on macroscopic aspects (like the IR pairs had done in the course lab). The IR pairs also shifted, but in their communication: The IR pairs became responsive (and the T pairs continued being responsive). In addition, the T pair that had been coherent in their reasoning during the course lab shifted from *intermittent* to *continuous* practice when they had access to the IR cameras in the modified lab.

The reasoning, in terms of quality, depended on the students rather than the tools (IR cameras) they were provided or the learning environment they acted in, as all students maintained the same quality in their reasoning in both the course lab and the modified lab. This is perhaps not surprising, as the IR cameras did not provide new facts (e.g. explanations) but rather gave them new ways of observing and more visual cues. In other words, they had more observations to discuss but were not provided with anything to improve the quality of their reasoning.

The results of the students' communication, practice, and content of the reasoning are more difficult to interpret. On the one hand, the differences between the pairs in the course lab suggest that the access to IR cameras in the learning environment of the course lab led to an active practice and communication, but also an exclusive focus on macroscopic aspects (which can be a problem depending on whether it is important for the students also to discuss submicroscopic aspects during the lab). In other words, the access to IR cameras "caused" the students to be exploratory in their practice and communication. On the other hand, one of the T pairs maintained the same type of communication and practice throughout both the course lab and modified lab (after getting access to IR cameras), and the communication of the students of the IR pairs shifted to responsive communication when they moved on to the modified lab, even though they had IR cameras during this occasion.

The shift indicates that the learning environment plays a role in how engaged students are with the activity (as it was changed between the course lab and the modified lab) and that students' cognitive resources (their preconceptions before the activity) are important in engaging students. This could explain why one of the T pairs maintained the same quality of reasoning, practice, and communication, even though they changed learning environments and gained access to IR cameras: If the T pair did not have the, in the terminology of this thesis, *epistemological resource* for *procedural regulation* necessary in engaging in a more continuous practice when getting access to the IR camera and were less conceptually acquainted with the content of the lab (i.e. lacked the necessary conceptual resources), they would maintain the same practice and quality of reasoning throughout the lab. The other T pair had an epistemological resource that allowed a shift in practice[27] and maintained the same quality of their reasoning throughout both the course lab and modified lab (they had the necessary conceptual knowledge or resources to discuss the content of the lab, which is reflected in their coherent reasoning).

[27] In the terminology of the thesis, this shift could be interpreted as a shift in procedural self-regulation.

## 6.3 Publication IV, Going through a phase: Infrared cameras in a teaching sequence on evaporation and condensation

Publication IV is published in the *American Journal of Physics*.

### 6.3.1 Context

Compared to II and III, IV 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 teaching 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.

The data in IV involve a group of five primary school teacher students that just had participated in a lecture in a physics teaching unit on heat, a part of the full semester course on science.

The students were introduced to a teaching sequence on *phase transitions* and *energy transfer*. The sequence initially involved four phenomena, and an *IR camera* was available as a supporting tool. Each phenomenon was embedded in a part (here A-C) that included an everyday situation and an experiment using an IR camera for observation.

The data was collected by video recording the students' interaction. An outline of the three parts can be found in Table 8.

*Table 8. The three parts of the teaching sequence in IV.*

| *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<br>Paper on cup<br>Shift paper on cup |

The instructional approach was based on POE. The sequence structure can be formulated as follows:

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

Each part was initiated by relating to a common everyday situation associated with a feeling of "warm" or "cold". This was then shifted to the experiments related to the sensations. Part C, which involved evaporation and condensation on a paper above a water surface, includes multiple parts of POE for the different shifts in the experiment (when moving around the paper to shift the equilibrium).

### 6.3.2 Analysis and discussion

The students' talk was dominated by exploratory talk but involved cumulative talk during the students' initial observations with IR cameras, when they shared the information gathered by looking at the IR camera. The information shared during the cumulation of shared knowledge was either readings of the IR camera (colors and temperature) or sensations (it feels warm, wet, or cold).

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 II, 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!" followed by "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 might therefore be more surprising to the students than the observations of parts A and B. The lack of previous experience with the outcome might have caused the more immediate reaction of referring to the semiotic resource of red to initiate the reasoning process, which was then translated into warmth through the 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"[28], 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.

The students anticipated the everyday situations that we contextualized B and C with: They activated an exemplar of stepping out from the shower and feeling cold in part A, the exemplar of leaving a glass of water for some time allowing the water to evaporate in part B and referred back to the two situations in part C in order to reason about evaporation. It was concluded that this indicated that the students had framed the sequence as a coherent whole around the concept of evaporation.

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[28] 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).

The students also encountered several barriers, even though they framed the whole teaching sequence coherently around the concept of evaporation. The barriers included a focus on equipment that was irrelevant for the lab, for example, an empty cup used to hold a paper and the focus on wind and air in the students' explanations.

## 6.4 Publication V, Productive resources in students' experimental investigation of phase transition: Inquiry with a grain of salt

Publication V is a manuscript prepared for submission and inclusion in a focused collection on instructional labs (*Instructional Labs: Improving Traditions and New Directions)* in *Physical Review Physics Education Research*.

### 6.4.1 Context

The study involved six pairs of students with a similar background in physics as they investigated what happens when salt is added to ice. When salt is added to ice (at room temperature), and the salt dissolves in the water, the ice will melt (faster) as the freezing point has decreased relative to the initial freezing point. The melting process requires energy which will decrease the surrounding temperature.

Three pairs were physics teacher students and three were engineering students. The teacher students had a similar background in physics as the engineering students but also had additional teacher-specific courses on teaching and learning. All the pairs had taken a course in thermodynamics.

The pairs participated in an ISLE-based lab activity, one pair at a time, investigating what happens when table salt (sodium chloride) is added to ice. The students were instructed to describe their initial observations, formulate hypotheses for those observations (at least two hypotheses), design experiments to test them, and carry out the experiments and potentially reject hypotheses. New observations during the stage in which they tested their hypothesis would generate a new round of observation, hypothesis, design, and performance of experiments, and potential rejection of hypotheses. The lab activity was not part of a course and was arranged outside their regular lab environment (in a room at our research facility).

The students did not initially have access to any equipment or material other than a paper describing the stages of ISLE. They were allowed to use any potential material or equipment that they could come up with when designing the experiments. However, by modifying the designs, they had to adapt to the available equipment and material when they were given access to the selection we had made for the activity.

Students' activity was video recorded and subsequently transcribed. Each pair's activity was summarized in tables (an excerpt of such a table can be found in Appendix E), with potentially important resources that were activated during the students' productive activity (that led to a systematic investigation) noted in one column and their activity regarding the different stages (e.g. observations and hypotheses) in other columns. The more prominent resources in the table formed the categories for the thematic pattern analysis of the transcripts.

### 6.4.2 Analysis and discussion

The pairs of students with experience with ISLE, and courses on learning, (i.e. the physics teacher students) were generally more systematic than those who did not have such experience. We identified several resources that play a role in the students' productive activity. The three *epistemological resources* identified in this data were *metacognitive reflection*, *procedural self-regulation*[29], and *exploratory mindset* (*exploratory frame* in this thesis). The students mainly activated these to assess, direct and control their own reasoning and practice: The students asked each other questions for clarification, challenged each other's arguments, checked that they both had made the same observations or had the same ideas, and reminded each other what stage of the activity that they were working with in order not to lose track of how the activity is structured.

Many *conceptual resources*, mainly *exemplars*, were also identified. The conceptual resources were generally used either as a basis for a hypothesis or explanation or for comparison and recognition (in, for example, descriptions of observations). The concept of energy was important in relating the temperature decrease with the melting of the ice: In particular, the students used "requires energy" as a basis for reasoning about the relationship between the melting ice and the decrease in temperature.

Students used *semiotic resources* (e.g. talk, gestures, forms of equipment, or drawings) in mediating epistemological and conceptual resources, i.e. in order to establish a common basis of knowledge between each pair of participants.

All the students were engaged at least during some parts of the activity. However, only those that were experienced in ISLE (i.e. the physics teacher students) were continuously systematic in their approach to the activity. As the systematicity of the students aligns with the identified epistemological re-

[29] Procedural self-regulation toward ISLE. I will most often refer to this epistemological resource as procedural self-regulation but what I mean here is procedural self-regulation toward ISLE or some other inquiry-based instructional approach with a guiding structure.

sources, we suggested in the paper that the epistemological resources are important components of systematicity and, thus, in a broader sense, also important for critical thinking in physics.

# 7. Analysis and discussion of findings

In this chapter, I will analyze and discuss the patterns found across my different publications in the light of my conceptual framework (see chapter 2). Some patterns were found across the different publications.

**RQ1: What resources can support students' active engagement during labs of different degrees of openness?**

**RQ2: What resources can support students' systematic engagement during labs of different degrees of openness?**

**RQ3: How can potential challenges in labs of different degrees of openness be addressed?**

Cases from the publications are presented as examples of the patterns that answer these questions. Some cases can be brought up several times to highlight different patterns.

I will begin by characterizing the learning environments and give an overview of students' active and systematic engagement.

## 7.1 Degree of openness of the learning environments

All the empirical publications (II-V) involved IR cameras available for students' investigation of one or several thermal phenomena and inquiry-based lab learning environments with different degrees of openness.

Here, I will discuss the second aspect: Inquiry-based lab learning environments. I will distinguish between learning environment and instructional approach: While learning environment refers to the whole situation (e.g lab environment/activities, instructional approach, and lab material), instructional approach refers to the specific method or philosophy that informs the structure of the lab activity.

Two learning environments emerged from the students' own activity and decisions: The engineering students in II discovered a phenomenon on their own (without being instructed to do it in the lab manual). The engineering students provided with IR cameras during a course lab in III[30] had the option of choosing to use the IR cameras whenever they wanted and for whatever they wanted during their course lab.

There are six different learning environments used in the publications that involve students' activity in labs (first column in Table 9): What is referred to as the course lab in III, the modified labs in II (the learning environment in what is referred to as sequence 2) and III, the designed teaching sequence in IV and the ISLE-based activity in V, and the parallel learning environment involving the use of IR cameras during the course lab in III (for some of the students). Additionally, the engineering students discovered a phenomenon on their own in II, which resulted in a new learning environment when they began discussing potential hypotheses for their observation outside of the course lab instructions.

I will briefly describe the degree of inquiry of each of these lab activities using roughly some of the characteristics from the rubric of Buck et al. (2008):

- Problem (the topic of investigation).
- Theory (prior knowledge that is necessary for an investigation).
- Procedure (the experimental procedures).
- Result analysis (how to interpret and analyze data).

The other characteristics, communication, and conclusions, were not a part of any learning environments and are therefore not included in the characterizations.

Some characteristics might only be partially provided, for example, if theory is provided about some lab tools but not the phenomenon to be studied. It will be counted as half-provided if it is partially provided (e.g. knowledge about the tool is provided but not about the phenomenon).

If 4 indicates a completely open lab (authentic discovery) and 0 indicates a fully scripted lab (confirmation lab), each of the used learning environments in my studies can be given a rough score to compare the degree of openness.

The scores are not definitive but should be seen as a way to compare the learning environments. The result of such a characterization can be found in Table 9.

[30] In contrast with the engineering students in III that were not provided with IR cameras.

*Table 9. Rough characterization of the degree of openness of learning environments in II-V.*

| *Learning environment (publication)* | *Characteristics not provided* | *Relative degree of openness (0-4)* |
|---|---|---|
| *The modified lab (III)* | Procedure partially | 0.5 |
| *Course lab (III)* | Results analysis | 1 |
| *The modified lab[31] (II)* | Theory, procedure partially | 1.5 |
| *The teaching sequence (IV)* | Theory, results analysis, procedure partially | 2.5 |
| *The parallel lab with IR cameras during the course lab (III)* | Problem, theory, results analysis, procedure partially | 3.5 |
| *The ISLE-based learning environment (V)* | Theory, procedure, result analysis, problem partially | 3.5 |
| *Engineering students' discovery (II)* | Problem, theory, procedure, results analysis | 4 |

In the modified lab (III), the students already knew about most of the outcomes of the experiments, which can be seen in the following exchange:

> Researcher: What type of phenomena will we observe here?
> Ike: One reaction is exothermic so it will become warm and the other is endothermic so it will become cold.
> Researcher: Yes, is there anything else we will observe?
> Ike: Perhaps transfer of heat from the cup to the table?

The same goes for the students in the other modified lab (II) that had already formulated explanations for the result in the previous learning environment. However, in contrast to the students in III that already had used the IR camera, these students encountered a novel observation when provided with the IR camera.

In the parallel lab (III), the modified lab (II and III), and the teaching sequence (IV), the students were provided with IR cameras to use in their investigation. However, they had some (the modified labs) or a lot (the teaching sequence and parallel lab) of freedom in how they could use them (thus, the procedure is partially provided).

In the ISLE-based learning environment (V), the students were provided with an initial phenomenon but later discovered one (thus, that the problem is partially provided).

[31] The learning environment in what is referred to as sequence 2 in II.

## 7.2 Overview of students' active and systematic engagement

Students can be active without being systematic and systematic without being active, or can be both active and systematic. I have categorized the cases of each learning environment (i.e. the engagement of the students that act in each learning environment) in the boxes of the diagram in Figure 6. Passivity is here related to the apparent lack of meaning making. The cases are categorized based on my interpretation of each case (based on my observations of the raw data and the interpretation of the processed data) and the students' activity in those cases.

The case of the engineering students (II) is more complicated to place in the diagram as the students participated in two very short activities in two different learning environments: the first being an activity that emerged from their own novel discovery during their course lab, resulting in the most open learning environment, and the second being an activity that was more railroaded (i.e. they were provided with an IR camera and instructed to observe the same phenomenon with it). This led to the students engaging in *exploratory talk* during their own discovery and *cumulative talk* when accessing the IR camera. They related both observations (without IR camera and with camera) to their experiences and thus showed that they recognized certain aspects in the observations, thus displaying active engagement. They also carried out the activity with IR cameras quickly and directly and built on their previously stated hypotheses, so the engagement could be considered systematic. They did not, however, have the experience of inquiry as the participants in the other two cases that were categorized as both active and systematic (Instructors (II) and teacher students (V)). The combination of their own novel discovery and subsequent instant inquiry with the IR camera can have led to the students being both active and systematic even though they did not have the same experience with inquiry-based labs as the other two cases.

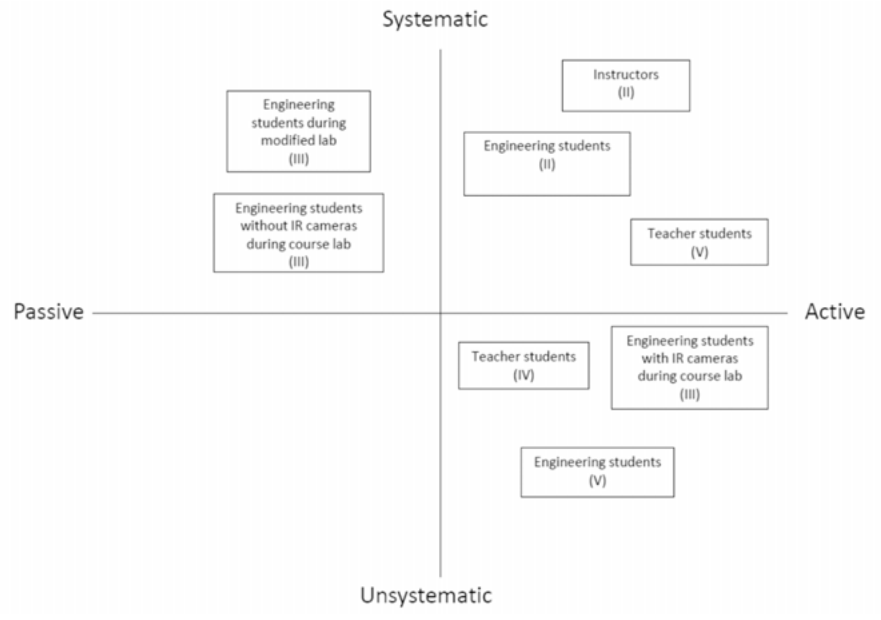


*Figure 6. Characterization of students' engagement in the different learning environments.*

## 7.3 Students' active engagement

Students are actively engaged with an activity when they investigate ideas on their own initiative: For example, when they engage in exploratory talk or initiate discussion on their own, activate exemplars, and use equipment to test some idea. Scherr and Hammer (2009) describe some signs of students epistemologically framing an activity as engaging in discussion: If the content of students' speech includes novelty, intellectual insight, or that they relate to their experience. According to Scherr and Hammer, the partner shares this framing if they respond similarly.

In this thesis, I characterize active engagement mainly as conceptual and semiotic resources guided through instantiations of an exploratory frame (e.g. exploratory talk). Students' active engagement can be modeled with an instantiated resources triangle (Figure 7): Active engagement emerges from resources such as an exploratory frame, exemplars, and tools that afford instant inquiry. Thus, to promote active engagement, one should promote an exploratory frame, activation of exemplars, and the employment of tools that afford instant inquiry that relate and align well with the taught content.

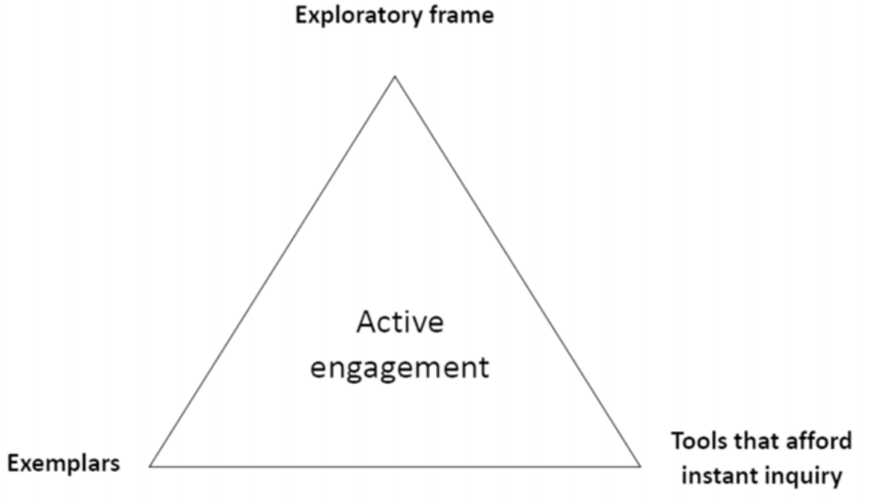


*Figure 7. An instantiated resources triangle for active engagement, that involves an exploratory frame, exemplars and tools that afford instant inquiry support active engagement.*

When students engage in exploratory talk, they tend to be active by asking each other questions and elaborating on each other's reasoning. When students discover novel things on their own, that they recognize some aspect of, they also tend to initiate talk about these discoveries. When students recognize aspects in what they observe or talk about, they can activate exemplars related to the aspects. Engagement in exploratory talk, self-initiated talk, and the activation of exemplars indicate that students are making meaning and explicitly showing this with their discussions. As meaning making is based on one's previous experience, i.e. cognitive resources, students making meaning should be considered actively engaged. I will give examples of these indicators of students' active engagement.

When I write about students being active, I mean that they are actively processing information from the surrounding and making meaning as observed from their communication. It is possible that students are making meaning but that it is not made visible to an observer.

### 7.3.1 Students' talk – finding novel things to talk about through collaborative engagement

Students' active engagement can be identified through their exploratory talk, which is an instantiation of their exploratory frame (another instantiation can be gesturing, see V). In other words, students engaged in exploratory talk are also active.

Exploratory talk is a form of dialogue that depends on "the kind of intersubjectivity that enables [collaboration partners] to achieve a shared understanding of the task in hand" (Mercer, 2008, p. 95). In other words, the semiotic resource from which exploratory talk emerges is dialogue, which mediates the epistemological resource of an exploratory frame. As an example, consider the following talk (excerpt from IV) between teacher students that discuss explanations for feeling cold when they walk out of the shower:

> TS 2: Then the heat would go out from the bathroom to the cold. It is that rule [...]
> TS 2: The second...
> TS 5: The second law of thermodynamics!
> TS 2: So the heat goes...
> TS 3: Out from the bathroom. And above all, you have gained a higher temperature than before so it will feel colder in the bathroom than it really is. You will experience it as colder because you are warmer.

The students' dialogue (in this case between more than two students) mediate their exploratory frame. Thus they engage in exploratory talk, building on each other's ideas while making their reasoning explicit. The exploratory talk allows additional resources to be activated, for example, the second law of thermodynamics as a conceptual resource in this case.

Exploratory talk is identified in the data of II, IV, and V in this thesis[32] to different extents. Students and instructors engage in exploratory talk both when they are actively engaged and when they are systematic, but in slightly different ways, as exploratory talk mediates different cognitive resources for active engagement compared to engagement that is both active and systematic.

Students' talk tends to be overall more cumulative and responsive in less open learning environments (e.g. cases of II and III) and more exploratory and self-initiated in more open learning environments (e.g. cases of III and V). In IV, which involved a medium degree of openness, students engaged in both cumulative and exploratory talk in different phases of the study, similar to the findings of Andersson and Enghag (2017). This could relate to the fact that less open learning environments include more direct instructions and thus fewer opportunities for students to make decisions and discoveries (for example, with the IR camera, like in III) on their own. The case of the instructors (II) is a possible exception as, although the learning environment was among the least open, they still engaged in exploratory talk for most of their activity. This can relate to the fact that they are much more experienced with inquiry than the students, which allows them to be freer in pursuing what piques their curiosity, like testing ideas that are not instructed. As such, the instructors engaged with the experiment similarly to the students in the most open learning environments (cases in III and V).

Exploratory talk is an instantiation of an epistemological resource: the exploratory frame. An exploratory frame allows students to test and build on each other's ideas. In other words, through the instantiations like exploratory talk and gestures, it ensures that all involved students are active. It has been suggested (Doucette et al., 2020) that it is important for students' interest and self-efficacy in physics labs that students share the workload of the lab evenly, i.e. that they engage in collaborative activities in which all participants engage equally in all the lab work and that lab designs should ensure this. A way of ensuring this is to let students practice an exploratory frame, which can be done through more open instructional approaches like ISLE (e.g. Etkina et al., 2010; Gregorcic, Planinsic, & Etkina, 2017) or approaches similar to ISLE in which skills that promote collaboration are taught directly, for example Thinking Together (Littleton et al., 2005; Mercer & Littleton, 2007).

It is possible to mediate an exploratory frame through other semiotic resources than dialogue, but "the distinctive role of spoken language in learning and development justifies it being given attention in its own right" (Mercer & Littleton, 2007, p. 1). In my studies, exploratory talk has a special role in that the form of talk is necessary for activating other resources during an active engagement. Exploratory talk can be described as dialogue that mediates an

[32] Exploratory talk was not a part of the analysis for IV. However, an additional analysis of the data in IV was included in the licentiate thesis to compare the publications in that thesis (II and IV).

exploratory frame (see Figure 8), thus allowing additional cognitive resources to be mediated through the exploratory talk (see Figure 9).

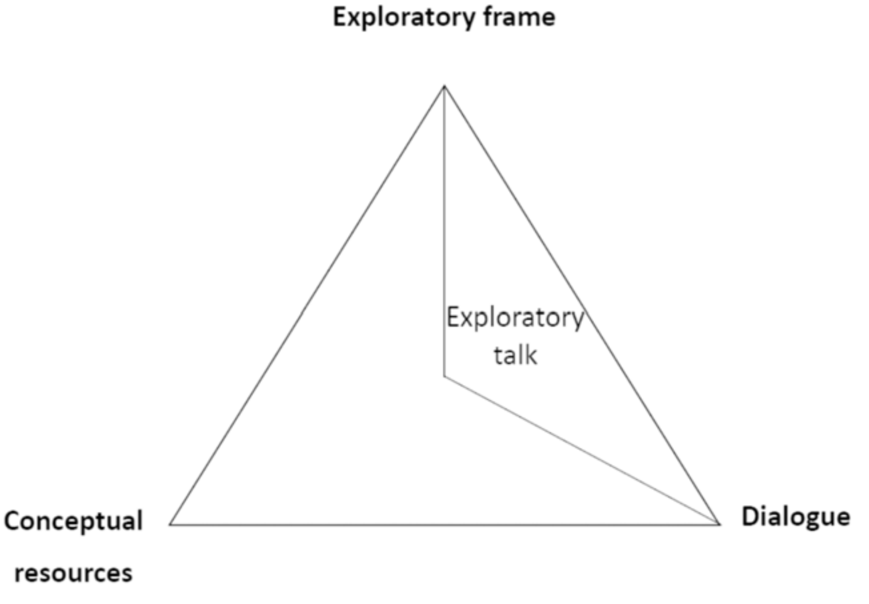


*Figure 8. Exploratory talk emerges from dialogue mediating an exploratory frame.*

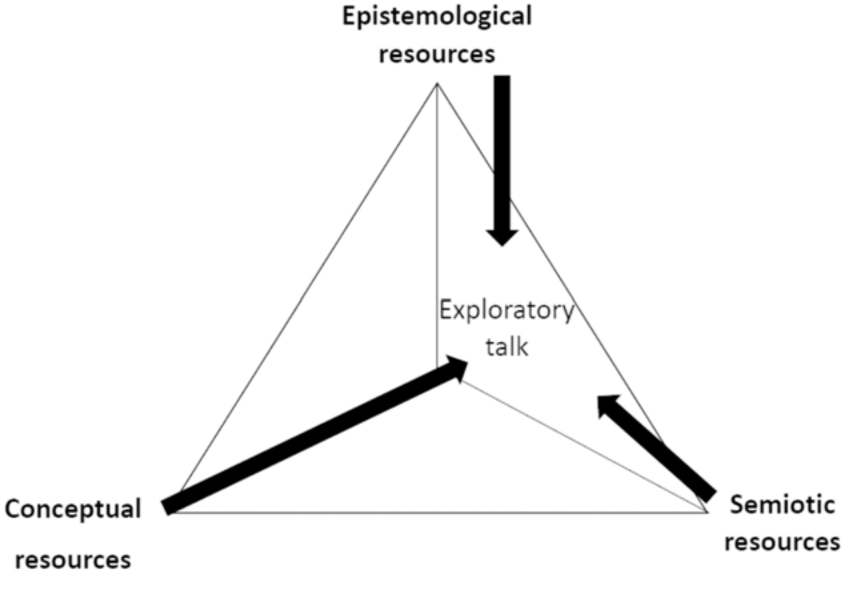


*Figure 9. Exploratory talk acts as a mediator for other cognitive resources and can coordinate cognitive resources with additional semiotic resources.*

There is a possible exception to exploratory (or self-initiated) talk being involved in active engagement in one of the cases (the engineering students during the modified lab in II). In this case (referred to as Sequence 2 in II), the students engage in cumulative talk (confirmation and repetition without elaboration) and are static in their approach to the activity. However, they are mentally active when they make an observation and then make a conclusion that involves one of their previously formulated hypotheses regarding moist sodium hydroxide. This exhibited passive behavior could result from the students framing the activity as instructed as they are railroaded in the activity. It could also be that they had already carried out most of the active work when they formulated their hypotheses (the reflective part), so it is now only a matter of confirmation for the students. In other words, the students are railroaded and do not find anything novel enough to break the instructed nature of the activity by engaging in exploratory talk. However, they can still be considered mentally active as they say "red is warm" when they observe with the IR camera and draw a reasonable conclusion (their confirmation). This makes this case complex as they are static in their behavior and maintain their cumulative talk even though they could be considered mentally active when they make meaning with the help of a semiotic resource of the IR camera (the color red).

More experienced participants could break the structure by changing their frame and engaging in exploratory talk during the modified lab, which is possible in the case of the instructors in II (see Figure 10). This change could also be a result of the instructors' physical engagement with the experiment and employment of semiotic resources, as they were more active than the students regarding the behavioral aspects of their activity (see Figure 16).

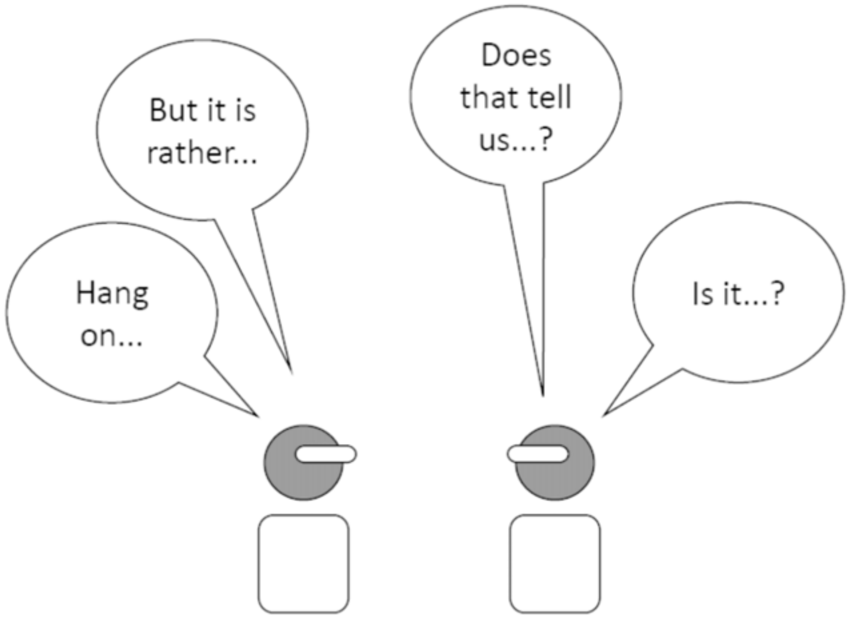


*Figure 10. Some characteristics of the instructors' exploratory talk in II.*

In a previous study that compares students' activity in a learning environment with a high degree of openness (ISLE) and a learning environment with a low degree of openness (referred to as nondesign lab), it was found that students in the open lab engaged in sense-making on their own accord much more often than students in the less open lab (the instructor prompted these students) (Karelina & Etkina, 2007). This aligns well with the results of my studies and, in particular, with the results in III, in which the students with IR cameras (the more open learning environment) initiated a talk about the lab on their own, during the course lab, to a higher degree than the students that carried out the instructed lab.

### 7.3.2 Students' exemplars – making meaning of physical phenomena

In my studies, I have found that exemplars, i.e. individual events, situations, or instances that participants draw on in the dialogue, are central for active engagement in that they are activated for comparison and, thus, recognition. In this way, the activation of exemplars displays meaning making. Students activate other types of conceptual resources in my studies but these are not as prominent or explicitly related to students' previous experience.

Students activate conceptual resources in their reasoning in all of my publications (it would be difficult to reason without conceptual resources). However, there is a clear difference in that exemplars are almost non-existent in the data of II and III, while it is much more common for all students in IV and V to activate this type of conceptual resource. This difference can be related to the fact that the phenomena that are central in II (deliquescence) and III (exothermic and endothermic reactions) are less common to think about in everyday settings than the phenomena in IV and V (the phenomena in IV were even contextualized with everyday situations) and exemplars would therefore have to come from the discipline itself. However, as the students are at the beginning of their education, they might not have formed or remembered exemplars from the discipline.

The more prominent exemplars that students activate when they are actively engaged in activities on phase transition in IV and V include the following situations:

- Feeling cold when they step out from a sauna or a shower.
- Leaving a glass of water overnight.
- Covering soaked lentils with a plate (and discovering condensed water on the inside).
- The salt and ice challenge.
- Adding salt to roads during winter time.
- Ice cream experiment from primary school.
- Caloric theory as taught in a thermodynamic class on the history of thermodynamics.
- A phase diagram from a thermodynamics class.

Some exemplars, like salt on roads, are activated across many contexts and situations[33] that involve the same phenomenon (Samuelsson & Haglund, 2022). The exemplars could be used to formulate a hypothesis, to make a pre-

[33] Some of my conference presentations include data that have not yet been published. Sixteen groups of students from seven different study programs, three different disciplines, and probed with two different methods have, in total, investigated salt on ice. 12 out of the 16 groups activated salt on roads as an exemplar in their investigations.

diction, or as a comparison with an observation in order to determine if a description of the observation is accurate: "And that [ice melting] is reasonable as you use salt on roads." (physics teacher student in V).

The exemplars are from everyday situations[34], outside of formal education, and from the formal education itself. Like other conceptual resources, exemplars are affected by the context and are generated "on the spot". As memories or collections of memories of specific events, they risk being affected by reconstructive recall (e.g. Redish, 2014) each time they are activated. In other words, exemplars are not copies of our experience from when we formed the memories but are reconstructed from fragments, just like all our other conceptual resources, according to the view on knowledge as fragmented mentioned in 2.2.1 Conceptual change (e.g. Brown & Hammer, 2013). An example of this can be found in the data of V where one student activated an exemplar of cooling beer:

> Student 2: I wanted to cool down beer really fast and I think that. This might be a myth that I've been tricked into believing, but I think that the salt...that I wanted to get ice really fast and I think I added salt to the water and then put it in the freezer which I think made me get the ice cubes faster than if I had not added salt to the water.

This later led the students to consider an assumption that could be problematic during the design of their testing experiments as it was based on a reconstructed exemplar:

> Student 2: Because I think that if water and ice are affected in the same way by salt then maybe we do not need anything that is ice cold. Maybe we just need a container with water that we can add a thermometer to.

The students later realized, through their experiments, that they had to reject the assumption. However, it still shows a potential problem with the fragmented nature of conceptual resources if students do not activate appropriate epistemological resources (more on this later).

The consensus in physics education research is that students bring many intuitive ideas to physics education, which emerge early in life when the child interacts with the world (Amin et al., 2023). In contrast, students can be quite aware of when they developed the basis for an exemplar, e.g. a specific experience in a classroom some years ago or a video they watched just a couple of days ago. However, they might also not be aware of when and how it emerged, in particular, if the exemplar is of a more prototypical (e.g. Nosofsky & Zaki, 2002; Rosch, 1973) nature.

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[34] "Everyday" in relation to knowledge can be ambiguous as formal physics may be an everyday type of knowledge for physicists who use this type of knowledge every day.

There is another interesting aspect in the activation of exemplars from everyday life: Lave's (1988) research showed that we could not take transfer for granted: although one might excel in mathematics at the supermarket, one can find it difficult when presented with an equivalent problem in a classroom situation, i.e. knowledge in the everyday situation might not be transferred to the classroom situation. Nevertheless, when students activate exemplars from everyday life to make meaning in a lab learning environment, they activate conceptual resources based on another context, in a new context. In a previous study (Samuelsson et al., 2019; R. Samuelsson, 2023), it was shown that a majority of students across several contexts activate the same exemplar (salt on roads) when they encounter (and reason about) the phenomenon of ice melting faster (in room temperature) when salt is added to it (i.e. freezing point depression). These activations of exemplars from everyday life are common in the physics lab contexts in my studies but not in the chemistry lab contexts, perhaps because the context itself is too specific to the discipline. Suppose students refine their exemplars so that they are more discipline-specific (e.g. Henriksson & Samuelsson, 2021). In that case, they might not be able to activate the same conceptual resources, that are based on everyday situations, in situations in the classroom (or lab) anymore. It should therefore be important that students keep activating exemplars from everyday life while refining the discipline-specific exemplars that are important in becoming a member of the physics community.

Apart from exemplars, other conceptual resources are important in all of the students' investigations: conceptual resources that are thermodynamics concepts, laws or principles (without relating to a specific situation where it was taught), and metaphors or analogies such as talking about areas with high temperatures as red (a metaphor previously referred to as Heat as Colour (Larsson et al., 2019)). Overall, comparisons with previous experiences (either direct or as metaphors) and recognition are important for students' engagement: When describing observations or formulating explanations, students are more active when they can find a basis in something they are familiar with, i.e. when they can make meaning about what they observe or explain. They can, however, remember words without giving them meaning and attempt to, for example, formulate an explanation, but in such cases, they do not engage in exploratory talk (see Figure 11). This can be a result of a metacognitive illusion: When a student remembers a word for something, they are tricked into believing that they have learned it (i.e. that they know the meaning that the word stands for) (Karpicke, 2009), which would be an argument for teaching the meaning of a concept before the technical term (Brookes & Etkina, 2015).

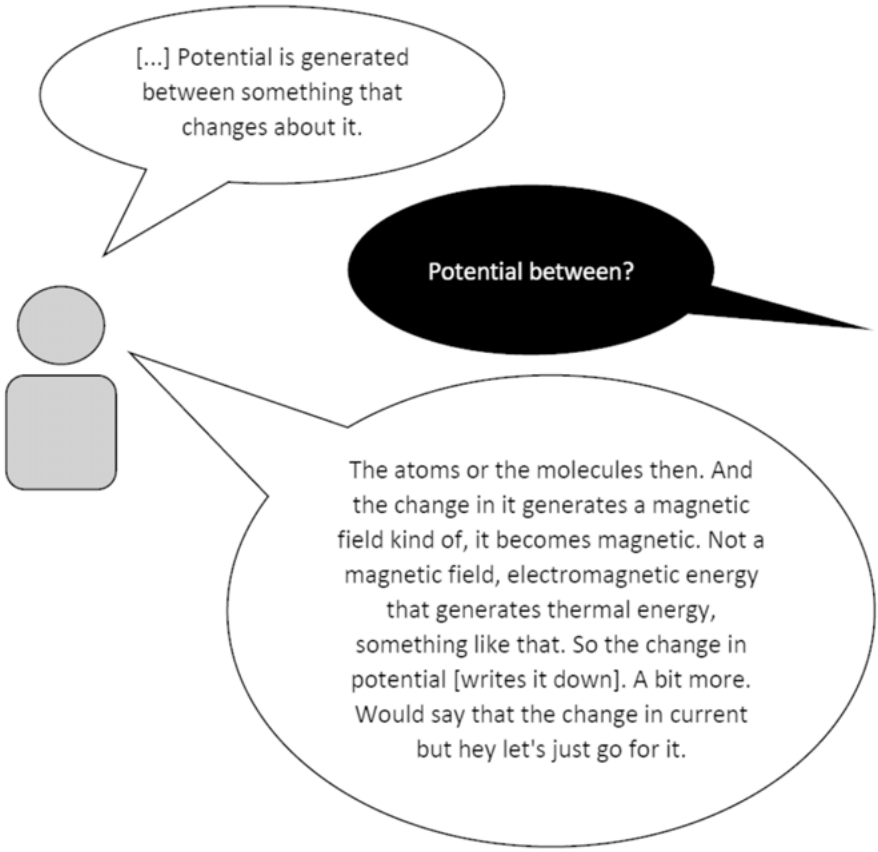


*Figure 11. Example (from V) of one engineering student (in a pair) attempting to formulate an explanation with words associated with physics. The researcher asks a clarifying question to which the student adds additional words.*

Previous research (e.g. Kang et al., 2009; Kidd et al., 2012) suggests that our curiosity is only fed by novelty up to a certain point. In other words, "curiosity is not directly related to the degree of surprise or novelty but instead follows a bell curve. […] We have no curiosity for the unsurprising […] But we are also not attracted to things that are too novel […] or so confusing that their structure eludes us" (Dehaene, 2021, p. 190). This is not a new idea: Piaget (1954) describes how novelty can be annoying if it is too unfamiliar. However, novelty with a smaller gap between what is new and the familiar can invite investigation. Students need to recognize something in whatever they discover, as they can not be able to talk about it otherwise. The activation of exemplars is an example of students recognizing something in their observation. Wickman and Östman (2002) describe a similar mechanism with their concept of *gaps* and what *stands fast*: When students find a gap (discover something novel or unfamiliar), i.e. a need for a new relation, in an encounter, they will attempt to establish such relations by filling the gap with comparisons to similarities and differences in previous experiences (what stands fast). In other words, the students find similar situations to relate to the novel encounter.

Hence, if the students in my studies would not have the experiences that could be used for comparison with their observations, there could be a potential problem in that their activity is hindered, i.e. the gap will linger (Wickman, 2004). This problem with novel discoveries thus lies in that students can easily become confused or frustrated if what they investigate is novel but completely unrecognizable. For example, when students do not have the conceptual resources to deal with the observation of the temperature when salt has been added to ice, they show surprise and confusion, as in the following excerpts from V: “We have discovered something insane”, “You will never believe it”, followed by an argument why it is not possible: “Even if salt decreases the freezing point of ice, why does the temperature decrease? I mean, if salt just decreases the freezing point, then it should begin melting right? But it should be the same temperature. Now the temperature is decreasing.” and “No okey, it gets colder and melts faster. This makes no sense. I give up”. In all of these cases, the students are experiencing what traditionally has been referred to as a cognitive conflict within the general conceptual change model (GCCM) (Posner et al., 1982).

Within GCCM, the conception of the novel phenomenon that a student encounters must be plausible for the conflict to be resolved (i.e. accommodation). According to Posner et al. (1982), there are five ways for the phenomenon to appear plausible: that it is consistent with students’ epistemology (the fundamental assumptions), that it is consistent with other knowledge, that it is consistent with previous experience, that the students’ can imagine how the world would be like if the phenomenon is possible and if it is possible to apply the phenomenon in some solution for a problem.

In the terminology of the resources framework (in contrast to the terminology of the general model of conceptual change (Posner et al., 1982), plausibility can be achieved if the students have epistemological resources to deal with the distrust or if the students can activate other conceptual resources (e.g. exemplars when it comes to specific instances of experience). Both of these ways to address this type of situation are included in my studies: Students that recognize the phenomenon through an exemplar (they make meaning) and students that activate epistemological resources to deal with this conflict (through systematic investigation). Activation of epistemological resources will be dealt with in 7.4 Students’ systematic engagement.

Some students avoid the distrust or cognitive conflict by activating an exemplar that fits with the observation, for example, an ice cream experiment in 6th grade or the salt and ice challenge when they observe a temperature decrease, or salt on roads (icy roads during winter) when they observe ice melting when salt is added to it. There are also cases of students that activate a conceptual resource to deal with experienced incompatabilities like how ice can melt and decrease in temperature simultaneously (in V) or how the sensation of cold from walking out from a shower relates to evaporation (in IV). Both situations are dealt with by relating the phase transition to energy transfer: "the phase transition [melting or evaporation] requires energy". In contrast to many of the exemplars, this is a conceptual resource which is easy to see that it is entangled with physics concepts, i.e. it loses its meaning without the concepts of phase transition and energy. Heron (2017) describes a similar idea when describing commonalities of models of conceptual change (misconceptions versus resources) in that some propositions given by students are entangled with physics concepts, and others are not (although the activation of these ideas, or conceptual resources, relate to the encountered physical scenario).

It is possible to activate a conceptual resource, like an exemplar, to deal with a challenge, such as a barrier. However, doing so is a short-term solution, acting as a shortcut, as it does not allow the students to develop their epistemological resources. Additionally, the activation of an exemplar that supports an observation can, for another observation, act as a barrier, for example, when a pair of students in V saw the decrease in temperature and exclaimed: "You can't decrease the temperature of the streets. That does not feel reasonable", thus activating salt on roads as an exemplar in order to argue for why they did not trust the observation.

Students' recognition and subsequent activation of exemplars that are in line with the physics that is to be taught can be leveraged in the design of teaching sequences as anchoring conceptions (Clement et al., 1989): When designing a teaching sequence on phase transition, suitable everyday situations (a sauna, a shower and water in a cup, labeled A, B, and C, see IV) were, in line with the resources framework (Hammer, 2000; Redish, 2004), chosen as contextualization for each experimental activity (see IV). The students anticipated each situation in the experiment by referring to the upcoming situation and, at the end, referred back to both previous situations (see Figure 12). This was, however, only done for evaporation.

The design with these situations matched the conceptual resources one could expect teacher students with this experience to employ in reasoning about evaporation. As an implication of this finding, it can be wise to consider the context of one problem or task and how the context varies from problem to problem in relation to the content it aims to teach.

Although this sequence led 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 can hinder productive resources in other contexts. For example, the ideal gas law (Brookes & Etkina, 2015; Leinonen et al., 2009; Loverude et al., 2002) has been found to hinder students' understanding of heat as a process or in employing the first law of thermodynamics. I call these kinds of resources barriers, a term that draws on an idea of Loverude et al. (2002, p. 146): "Their confidence in this law [the ideal gas law] seemed to be a significant barrier to consideration of the first law of thermodynamics".

Like previous research (e.g. Robertson et al., 2021) on students' conceptual resources argues, students' resources can be used as raw material for building more formal physics knowledge. The task for the teacher is to identify the resources that are productive in building the more formal knowledge. Leveraging students' common exemplars in designing instructions could be a great way of making physics more available to the students.

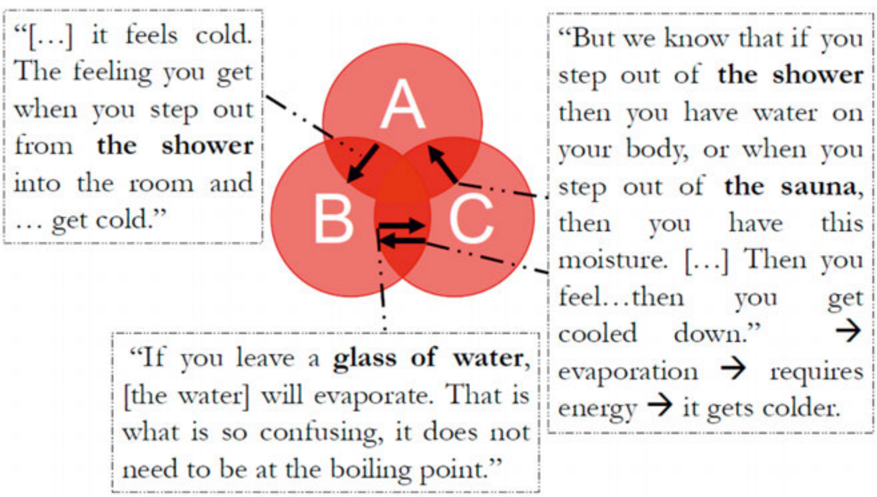


*Figure 12. The teaching sequence in IV involved three situations: A) Sitting in a sauna and feeling warm when pouring water on the rocks, relating to condensation. B) Stepping out from the shower feeling cold, relating to evaporation. C) Leaving a cup of water on a table, relating to evaporation (C). The students in IV anticipated each situation by referring to the upcoming situation in a previous part of the sequence and, in the end, referred back to the previous situations (see transcripts in the figure).*

### 7.3.3 Semiotic resources mediate conceptual resources

In my studies, I have found that the lab tools used by students (and instructors) have a central role in students' engagement. They all involve different types of semiotic resources, either mediating the conceptual resources that are activated by the students in reasoning together as a group or conveying information from the surroundings to the group (i.e. the gathering and processing of information). Tools like the IR camera can enable students to make novel observations about phenomena that have been mostly inaccessible to them before (like the transfer of heat) and simultaneously allow the students to relate the novel observation to something they recognize (colors).

It has been argued (Almqvist & Quennerstedt, 2015) that discussions on learning usually focus on either the mind (like mental models (Vosniadou, 1994)) or communication (the use of tools for communication (Schoultz et al., 2001)). It has also been suggested (Bernhard, 2018) that it is common to ascribe little cognitive value to lab tools, i.e. their role in mediating our experience is often neglected. This view has also been challenged (Bernhard, 2018; Tang et al., 2022), and my findings also challenge that.

Semiotic resources that convey information from the surroundings can lead students to form new conceptual resources, i.e. manipulation of tools for idea generation (Tang et al., 2022) or instant inquiry (Haglund, Jeppsson, et al., 2016). In this sense, lab tools, and other collections of semiotic resources, have a cognitive value in that they become part of our cognitive process when we employ them as an extension of the mind (Clark & Chalmers, 1998).

The employment of semiotic resources is, together with the mediation of conceptual resources, a part of students' active engagement. Zittoun and Bringmann (2012, p. 1809) describe students making meaning as students "drawing on their history of similar situations and on available cultural resources", i.e. the comparison with previous similar situations, but also the engagement with available historical resources – the semiotic resources employed by the students. In this sense, semiotic resources and, by extension, lab tools are important for students' cognitive processes.

Based on the cases in my studies, I suggest that there are at least two indications of lab tools and other collections of semiotic resources, like our bodies, being part of students' cognitive processes: That students mediate their conceptual resources through semiotic resources when communicating meaning, and that students associate, or activate, conceptual resources when they attend to the semiotic resources to make meaning.

In general, and in line with the argument of Mercer and Littleton (2007), students' speech is particularly important for learning and development. Students' speech addressed previously in this chapter is central for mediating conceptual resources, but other embodied semiotic resources are also important for this purpose. Students can, for example, use specific gestures (see Figure 13) to mediate a conceptual resource (the freezing point of water at 0 degrees Celsius) in order to collaboratively make meaning about a scientific concept (freezing point depression). In this case, the two students collaboratively build on each others' gestures. Previous research (e.g. Euler et al., 2019; Tytler et al., 2021) has emphasized the importance of body-based semiotic resources in meaning making of physics concepts when students investigate physics topics in inquiry activities.

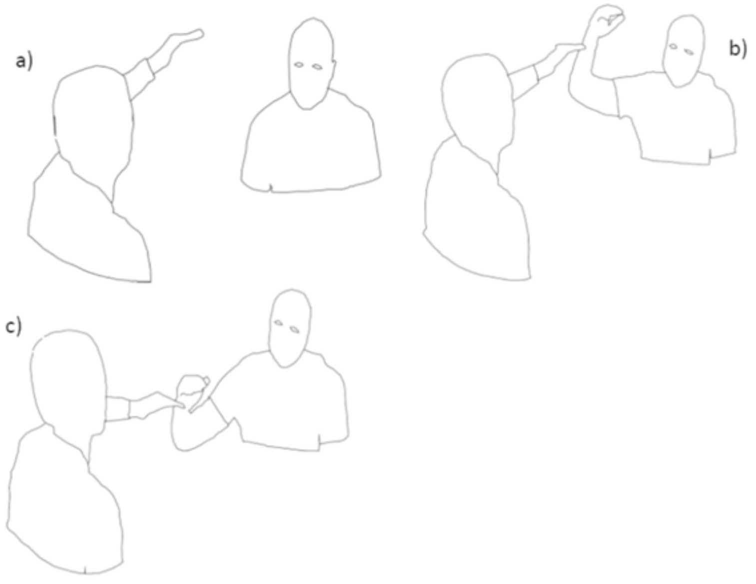


*Figure 13. Figure from V. Two physics teacher students, a) and b), mediate the conceptual resource of a freezing point at 0 degrees Celsius with gestures, and c) indicate a freezing point depression.*

Students can also activate a conceptual resource based on the attended semiotic resource, through recognition, as in the case (see Figure 15) when a pair of engineering students (II) got access to IR cameras to study a phenomenon for which they previously had proposed hypotheses. The students quickly activated a conceptual resource (red is warm) when they observed the thermal image and its colors. This led them to confirm one of their hypotheses (exothermic reactions are warm and thus red). The teacher students (IV) followed a similar line of reasoning when they observed, with an IR camera, a paper being put on top of a cup with water resulting in a temperature increase due to condensation: They exclaimed, "It became red!", and concluded, "Yes, the paper became warm!". The engineering students (II) also observed that the texture of a salt (NaOH) looked "melting" or "sticky" compared to what it looked like before. The students pointed out their observations with a gesture (see Figure 14). Another pair of teacher students (in V) used their hands to touch the salt added to the ice, and felt that it was colder than the ice without salt. They quickly activated an exemplar (an ice cream experiment that one of the students remembered from $6^{th}$ grade), related to this observation which, in this case, acted as a semiotic resource (cold sensation).

In other words, all these students recognized something in the novel observation. The red color as a semiotic resource affords attention to the thermal phenomenon and allows the students to relate to the novel phenomenon. In the case of the observation of the salt's texture, it is the texture that is the semiotic resource that is compared to their experience of "sticky" textures, and in the case of the sensation of cold, the students recognize the phenomenon from a previous experiment.

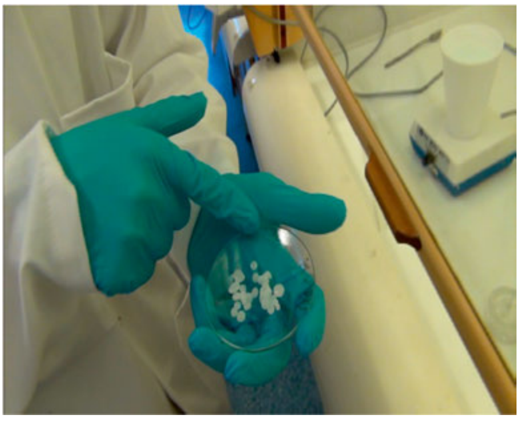

*Figure 14. Figure from II. Engineering students discover a change in the salt texture (e.g. it is "melting") they are working within the lab.*

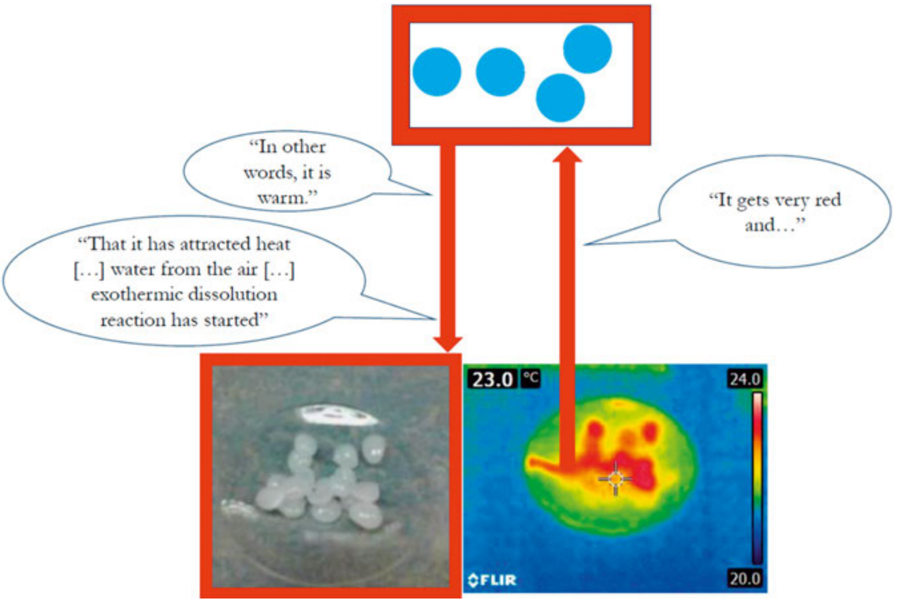


*Figure 15. A pair of engineering students (II) study deliquescence (a hygroscopic salt, NaOH, reacting with water from the surroundings) with an IR camera and make a quick association (i.e. activate a conceptual resource) to what they observe in order for them to confirm a previously formulated hypothesis.*

The instructors' (II) dynamic use of the IR camera in Figure 14 relates to what has previously been discussed in terms of *instant inquiry*, i.e. that the intuitive character of the tool invites students to immediately act upon their curiosity

(Haglund, Jeppsson, et al., 2016). The instant inquiry emerges from the combined affordances of the semiotic resources of the IR camera, like the spatial mobility (affordance of the form) and the attention to thermal aspects or filtering function (affordance of the colors). However, it can also be related to the wow factor (Chandler, 2009). In a way, tools (collections of semiotic resources) that afford instant inquiry allow for testing a conceptual resource.

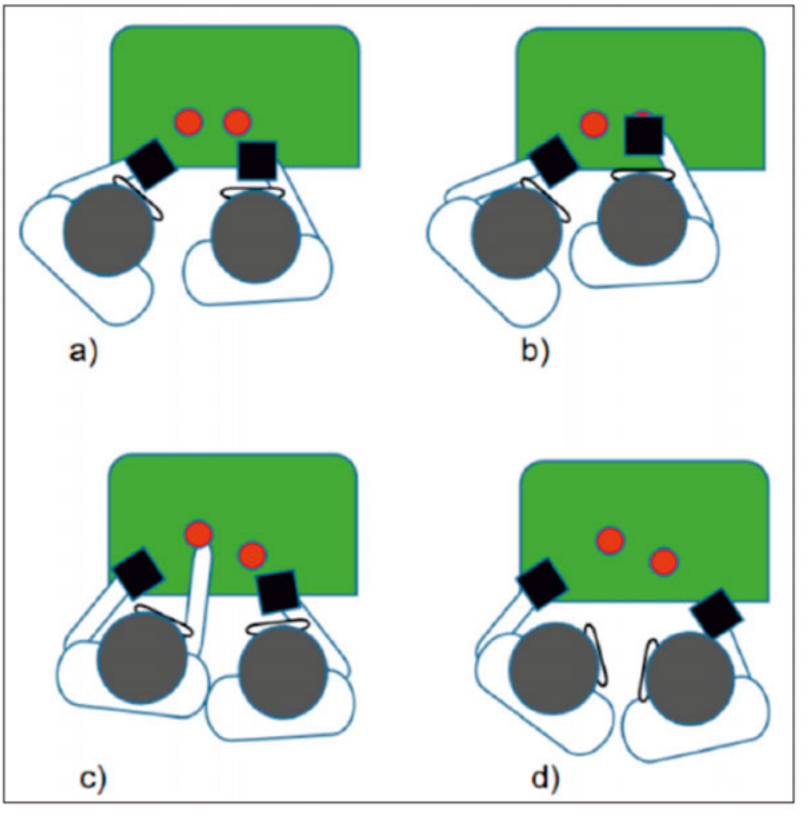


*Figure 16. An example of how IR cameras afford instant inquiry. a) The initial positions of the instructors. b) The instructors began exploring the phenomenon before even being instructed about what to do and c) moved around both IR cameras (black squares) and the rest of the lab material (red circles) in order to make additional observations. They looked at each other during the more intense discussion. The figure can be found in II.*

The most prominent case of instant inquiry in the studies was the engineering students' use of IR cameras during the course lab (III). These students had complete freedom in how and when they wanted to use the IR cameras. A sustained interaction with the experiment emerged from the students' self-initiated talk (involving their initial ideas), instant inquiry, and novel discoveries – a novel discovery (e.g. a transfer of heat from the magnetic stirrer and the insulation of the calorimeter) forms the basis of new discussions, which leads to additional instant inquiry with the camera, i.e. a self-feeding inquiry cycle is formed that keeps the students actively engaged, compared to the students that did not have IR cameras in the lab.

Affordances are related to cognitive resources: e.g. how the IR camera is moved is affected by how students frame an activity and interpret and make decisions based on the color scheme related to their conceptual resources. In other words, affordance relates to meaning making.

There are two types of affordances related to meaning making among the semiotic resources employed by the students and instructors: The first type involves communication from a sign maker with an intention, and the second type involves interpretation of environmental input without an obvious sign maker (see Volkwyn (2020) for a similar discussion). Communication from a sign maker with an intention can be conceptualized as semiotic resources that mediate cognitive resources. In turn, interpretation from environmental input entails semiotic resources that convey information from the surroundings.

Generally, in my data, students are less active in less open learning environments, which in turn allows for less freedom in doing things, i.e. employing semiotic resources. The pair of students in the modified lab in II is an exception as they, although acting within a less open learning environment, engage with semiotic resources that are easily relatable (they have a high pedagogical affordance (Airey, 2015; Airey & Eriksson, 2019). Additionally, they build on an activity they initiated through their discovery and subsequent hypothesis generation. Semiotic resources that convey information from the surroundings, like those of the IR camera, are much more common since all lab equipment that does any measurement involves these semiotic resources.

## 7.4 Students' systematic engagement

Structured and content-focused labs have been suggested to lead students to focus on the analysis of data and time management (Holmes & Wieman, 2018). However, more open labs that involve a high degree of inquiry require other cognitive processes and epistemologies than less open lab (Chinn & Malhotra, 2002). These other cognitive processes and epistemologies that are required for more open labs are what I, in this thesis, refer to as epistemological resources.

Systematic engagement involves a structured and coherent approach to the learning environment. The reasoning is coherent and easy to understand, each new phase of the students' activity builds on a previous phase (e.g. students base a hypothesis on a previous observation or a lab design around testing a hypothesis), and there is a direction in their activity. Students can be systematic without being actively engaged (for example, in a railroaded activity with less open instructions). However, in this thesis I take a particular interest in situations where participants are both active and systematic in their lab work.

Previous research has suggested several resources, sometimes referred to as epistemological resources (e.g. Richards et al., 2020), that relate to systematicity, for example, self-reflection and monitoring as metacognitive skills (May & Etkina, 2002), epistemic cognition (Shekoyan & Etkina, 2007, 2009) or a discovery mindset (Benson & Dresdow, 2003), that promote the thinking of alternatives and exploration of different perspectives. Additionally, research has emphasized the need to study how students think (Mercer & Littleton, 2007) and regulate their cognition, behavior, and motivation (Hadwin et al., 2017) together. An instantiation of the exploratory frame, exploratory talk, has also been described as "the embodiment of critical thinking" (Littleton et al., 2005, p. 70), i.e. relating to systematic engagement (Nygren et al., 2018). However, in my research, exploratory talk is not only important for systematic engagement but also for active engagement, as in the case of students' gesturing to illustrate freezing point depression (V).

May and Etkina (2002) claim students do not develop metacognitive skills through problem-solving if the answers are known. The other way around, open inquiry labs should promote metacognitive skills and thus the development of epistemological resources. Students that mainly rely on conceptual resources to deal with barriers or other potential challenges, during their activity might not develop the epistemological resources that lead to a more systematic approach in more open inquiry-based lab activities.

In my research, I have identified three important epistemological resources for systematic activity during inquiry activities: An exploratory frame; metacognitive reflection, and; procedural self-regulation[35]. It is possible to model students' systematic and active engagement[36] with an instantiated resources triangle (see Figure 17).

At least two cohorts in my studies show signs of activating these resources during their activity: The instructors (II) and the physics teacher students (V). Therefore, they are the cases I will mainly write about in this thesis section.

[35] Again, procedural self-regulation toward ISLE. I will most often refer to this epistemological resource as procedural self-regulation, but what I mean here is procedural self-regulation toward ISLE or some other inquiry-based instructional approach with a guiding structure.
[36] Students that are intrinsically systematic are also active.

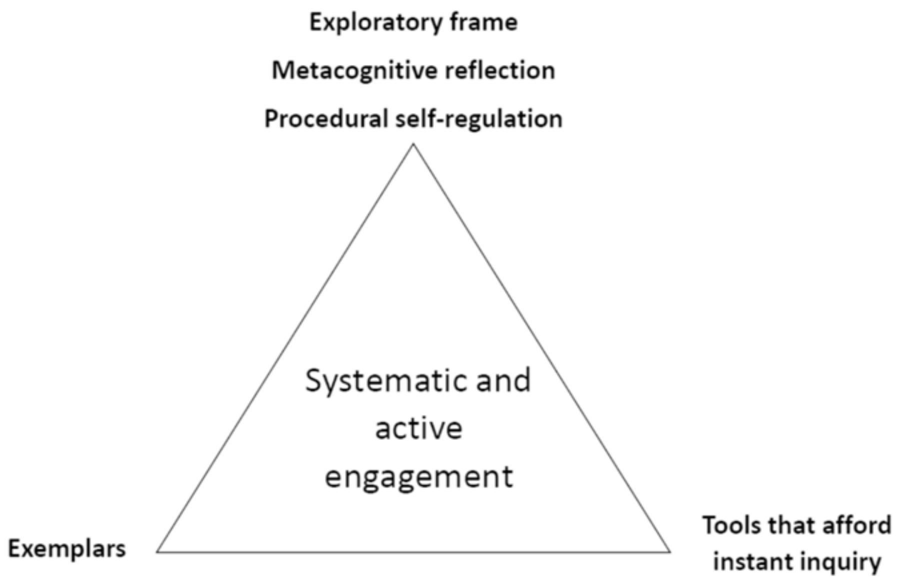


*Figure 17. An instantiated resources triangle for systematic and active engagement. An exploratory frame, exemplars, and tools that afford instant inquiry support active engagement. Metacognitive reflection, procedural self-regulation, and an exploratory frame support systematic engagement.*

### 7.4.1 Experience with inquiry-based labs helps to deal with inquiry-based activities through exploratory talk

In my studies, participants with experience in inquiry-based labs were more often systematic than those without this experience. An exploratory frame instantiated as exploratory talk is here once again central but with additional epistemological resources (procedural self-regulation and metacognitive reflection) supporting systematic engagement.

The instructors (II) are systematic in their activity and open up the activity by describing the phenomenon before they are instructed what to do, adding a question that can be elaborated on:

> Instructor 2: You see that already when it dissolves water from the air, so it is enough to give an indication. Does that tell us something about the reaction or the cameras? I don't know.
> Instructor 1: The reaction I think.

Their continued discussion is a great example of exploratory talk's elaborative nature (based on an exploratory frame as an epistemological resource). One instructor explains the phenomenon which the other instructor challenges. This, in turn, leads to an elaboration (see full transcript on page 10 in II):

> Instructor 1: Sodium hydroxide dissolves in water.
> Instructor 2: Ehm, yeah, I would not call it that in this case.
> Instructor 1: But it is rather attracting water from the air but you will still get a dissolution reaction.
> Instructor 2: Is it water dissolving in sodium hydroxide in when it is here? […] there is more sodium hydroxide than the water you got, so it is rather than hydra…it goes into the crystal structure and hydrates.
> Instructor 1: Hang on we do not have that much left of the crystal structure on the surface, so there is not hydration in the crystal structure.

The instructors are also trained in inquiry as they (apart from being instructors) are researchers who do inquiry in their everyday work.

Exploratory talk in my studies (see Figure 18 for examples of characteristics from the data) involves questions and reasoning that is "more visible in the talk" (Mercer, 1995, p. 104).

Through the exploratory talk, students can co-reason by challenging ideas, evaluating evidence, and negotiating to reach a common understanding (Mercer, 2008). The key here is that reasoning is made explicit through the talk. By engaging in exploratory talk, students allow other students to evaluate the reasoning and build on the reasoning. However, exploratory talk is not a guarantee for systematicity, as there are instances of students engaging in exploratory talk without being systematic, for example, the engineering students in V and possibly the teacher students in IV. It is thus not sufficient for students to engage in exploratory talk for systematicity. Additional epistemological resources (other than an exploratory frame) can be mediated through the exploratory talk or semiotic resources coordinated with the exploratory talk.

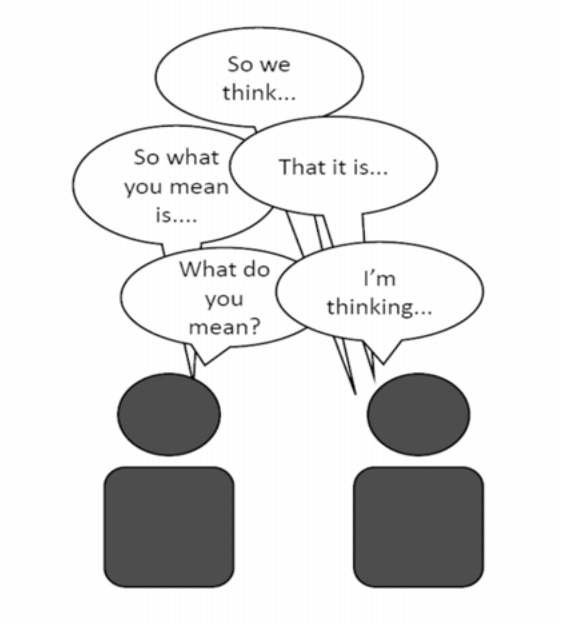


*Figure 18. Characteristics of exploratory talk as seen in the opening lines of students engaging in exploratory talk in V.*

The students in V all participated in a highly open lab. However, the teacher students were more active in engaging in exploratory talk than the engineering students, that more often asked, or had to be guided by, the researcher in the room (see Figure 19) or even engaged in reasoning that was difficult for the researchers to interpret (e.g. "technobabble"[37]). The difference between the engineering students and the physics teacher students could be explained again by their previous educational experience, like experience in inquiry-based labs. Previous research (Etkina et al., 2006) has suggested that experience with ISLE (like the teacher students in V had) leads to the acquisition of experimentation-related skills such as analytical, communicative, and evaluative skills and that the acquisition of these skills from experience with ISLE activities is transferable to other contexts.

[37] A term common in science fiction, like Star Trek, for the talk that uses terms that sound technical but do not carry any meaning, i.e. imitation of technical terminology.

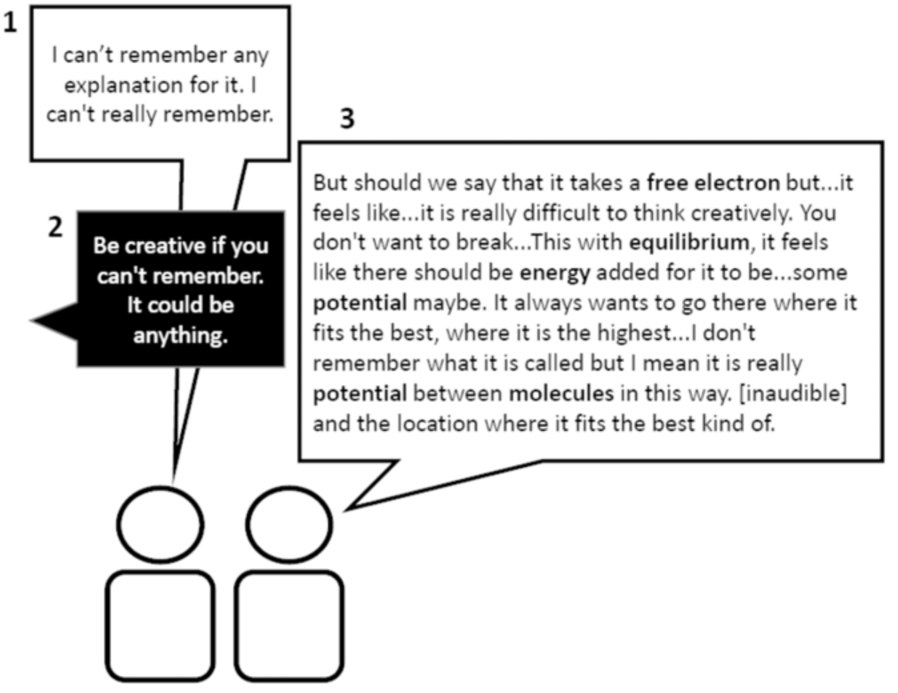


*Figure 19. The engineering students in V did not have experience with ISLE and did not engage in exploratory talk to the same extent as the teacher students. They even engaged in "technobabble" at times, i.e. they used technical terms about which they did not seem to be able to make meaning. The boxes are to be read in the order 1, 2, and 3. The black speech box (2) is the researcher.*

The engineering students in II are an interesting and more complex case. When the modified lab and course lab are considered together, the students' overall engagement can be described as active and systematic. They are actively engaged when they make the novel observation of the moist NaOH on their own during the course lab and systematically engaged when given access to the IR cameras. However, in contrast to the teacher students (V) and instructors (II), they do not have any experience with inquiry-based labs. A potential explanation for why they still were able to engage both actively and systematically could be found in the openness of the two learning environments: The students have much of freedom in formulating hypotheses and describing their observations when they initially encounter the phenomenon (deliquescence), as they in a way own the activity when they discover the phenomenon outside of the instructions of the course lab. When subsequently observing the phenomenon with IR cameras, they have less freedom in terms of what they can do. However, they have also carried out some of the work already when formulating hypotheses (i.e. they have to reject or support their hypotheses). It is possible that the case of the engineering students in II could provide a clue about how to introduce students to inquiry-based labs. By designing a lab learning environment in which some of the characteristics or stages are more open than others, and others have a low degree of openness, students can both explore ideas freely and practice epistemological resources for systematicity.

### 7.4.2 Addressing encountered and potential challenges

Challenges, such as cognitive conflicts, can be addressed more short term by leveraging students' conceptual resources, e.g. contextualizing problems with common exemplars and providing students with appropriate and intuitive tools (tools with high pedagogical affordance (e.g. Airey & Linder, 2017)). However, this does not allow students to develop and practice the epistemological resources that can support them in dealing with challenges in the future.

In their critique against minimally guided instructional approaches, Kirschner et al. (2006, p. 75) mention students' "prior knowledge" that provides "internal guidance" as critical for working with less guided activities. I argue that this internal guidance is provided through the epistemological resources that students develop if they gain experience with inquiry-based activities such as ISLE and that encountered barriers are important in developing these resources.

The first example of an epistemological resource important for systematicity has already been touched upon: an exploratory frame. This quite large epistemological resource is best compared to what has traditionally been referred to as a frame or framing (Haglund et al., 2015; Redish, 2004; Scherr & Hammer, 2009) or a mindset (Benson & Dresdow, 2003; French II, 2016), in particular epistemological framing as described in III. It is possible to mediate this epistemological resource through different semiotic resources, for example, dialogue or different types of gestures, both on their own and together.

We return to the example (see Figure 20) of two students experienced with ISLE, who make meaning of freezing point depression by coordinating gestures (as exploratory gestures), dialogue (as exploratory talk), and conceptual resources, such as freezing point, which are mediated by the exploratory talk. The example will now also focus on epistemological resources involved in the activity.

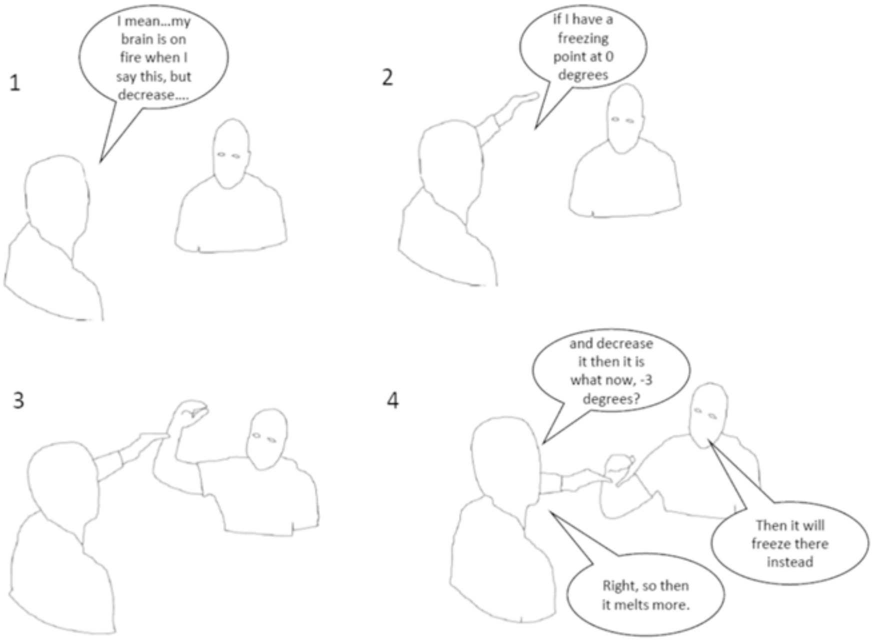


*Figure 20. Two physics teacher students experienced with ISLE were not sure what freezing point depression was and began investigating this (in order 1-4) by building the concept from its components (freezing point and a scale of temperature), i.e. they made meaning of freezing point depression by activating epistemological and conceptual resources that they mediated through dialogue and gestures.*

The students initially encounter a problem in that they do not remember what freezing point depression is, which is indicated by a metaphor ("the brain is on fire"). The students collaboratively overcome this problem by activating both epistemological and conceptual resources and employing the appropriate semiotic resource to mediate their cognitive resources.

There are other occasions where students (and instructors) had to deal with different problems or barriers during their activity. I have previously mentioned that conceptual resources can be used as shortcuts in dealing with encountered problems but that this might not help the students practice and develop epistemological resources that support systematic activity in inquiry-based labs. Another way of dealing with barriers is through procedural self-regulation and metacognitive reflection mediated through exploratory talk or other semiotic resources. Procedural self-regulation (toward ISLE) and metacognitive reflection are two of the epistemological resources I identified in V as important for systematicity.

Procedural self-regulation can be exemplified through two cases: the instructors (II) and the physics teacher students (V). The instructors use formulations such as "You see that" and "it is your turn to talk" and the students use similar cues related to the stages of ISLE, to procedurally self-regulate toward ISLE in their activity (see Figure 21).

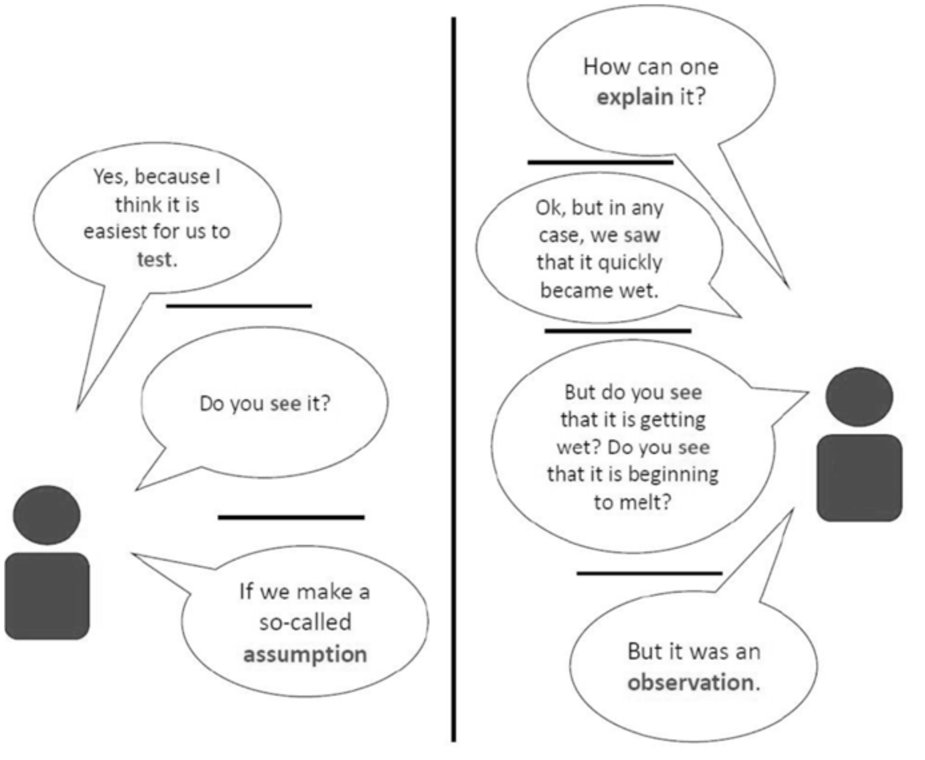


*Figure 21. Characteristics (cues) of procedural self-regulation (toward ISLE) from V. The epistemological resource serves to direct or guide the activity of the students by making the practice and goals explicit through their, in this case, exploratory talk.*

The example in Figure 21 can be contrasted with students that do not have experience with an inquiry-based lab learning environment that they can guide their activity with or students that framed the activity as instructed. The students without experience of ISLE (V) lacked systematicity in their activity. They sometimes came up with explanations without relating them to an observation or design experiments without an explanation to test. They would also sometimes ask the researcher in the room questions. In those instances, the researcher had to guide them by cueing with the stages of ISLE (see Figure 22).

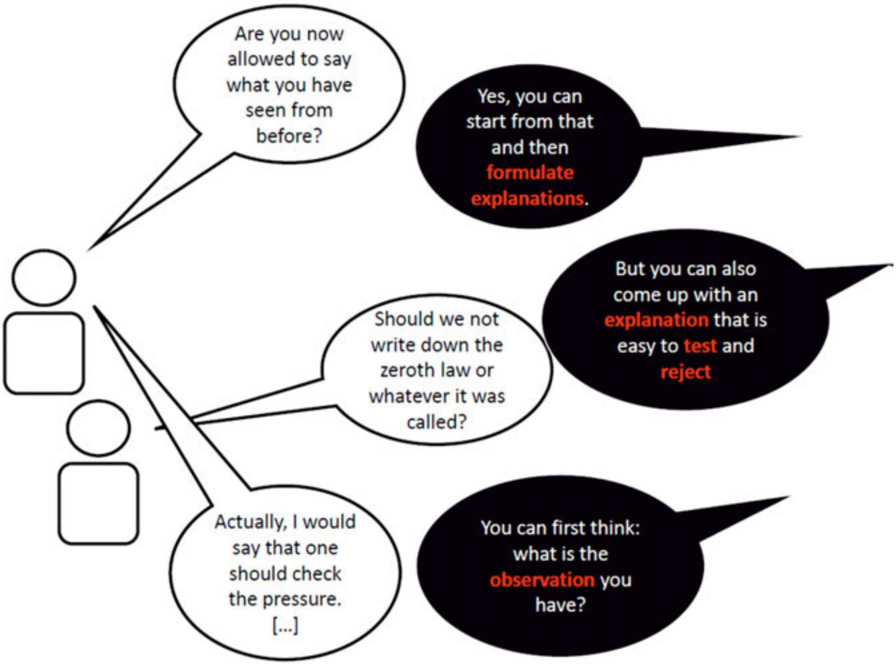


*Figure 22. The students (white speech bubbles) that were inexperienced with ISLE (V) were not able to guide their activity through a framework like ISLE and instead asked the researcher (black speech bubbles) in the room for guidance or had to be guided by the researcher when they forgot what they were supposed to do (i.e. they used the researcher for guidance). The researcher asked the students questions about what they could see, explain, or test but never provided them with the observations, explanations, or designs).*

The last epistemological resource is metacognitive reflection which involves the reflection on the nature of knowledge, the organization of knowledge, and knowledge-related roles or situations, like when the physics teacher students (V) were formulating a hypothesis for an observation and explicitly referred to the knowledge type of the hypothesis: "I feel like I am thinking more about an everyday type of explanation than physics now", or their role related to knowledge: "I am thinking that if I am a student, and as I thought when I was in 6th grade […]". Additionally, students mediating the metacognitive reflection through exploratory talk might pose questions like "What do you mean?" and "And how do you think in this instance then?" about each other's meaning making, pushing the collaborative activity forward systematically. The ability to ask the right questions reveals something about the knowledge of the "asker" in that they are "at an appropriate distance from the given material" (Miyake & Norman, 1979, p. 363). In other words, when students can ask each other questions, they display social symmetry; they "recognize each other's right to participate and respect the potential validity of each others' contributions" (Mercer & Wegerif, 2001, p. 88). Social symmetry is important for students' reasoning in collaborative activities (Light et al., 1994).

Instances of metacognitive reflection being mediated through exploratory talk involve explicit questions and talk about knowledge and its interpretation, reconsiderations and moments of realization, and explicit talk about students' roles or situations regarding their knowledge. Examples of this include students' descriptions of reasoning as "intuitive" and "from a student perspective" or "during my last practice course", explicit talk about explanations: "You are explaining to yourself what I am trying to say", being explicit about one's reflection: "I need to organize some things in my head", and sudden realizations: "Wait!". The instructors (II) also show signs of this epistemological resource when they encounter a potential challenge (see Figure 23) in that one instructor's explanation is questioned by the other: They disagree on how to describe and explain the phenomenon (deliquescence). Each instructor handles this potential challenge by referring to the difference in their identities as researchers (i.e. their specializations in terms of expertise).

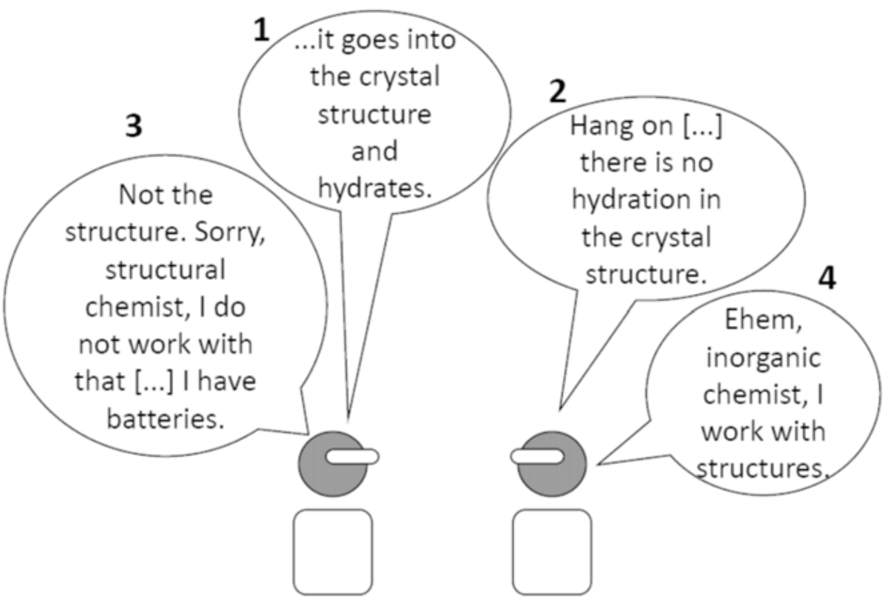


*Figure 23. The dialogue should be read in order 1-4. The instructors solve an encountered potential barrier by referring to their identities as researchers.*

When students encounter a potential challenge during a lab activity, they can deal with it through conceptual resources and/or epistemological resources. The case above exemplifies how it is possible to deal with a challenge with epistemological resources. Dealing with a barrier through conceptual resources can be a shortcut (dealing with it mainly through recognition) that can be useful in the short term, but that gives few opportunities to practice and develop epistemological resources. In one of my conference presentations (Samuelsson, 2021), in which I did an additional analysis of the data from IV, I identified semiotic resources in the environment that led to the activation of resources that acted as barriers for the students' reasoning process (see Appendix G or (Samuelsson, 2021)). I proposed two ways teachers can deal with this in designing a teaching sequence: By removing or adding information to the environment. Removing something that leads students to activate barriers makes the learning environment more accessible to students. Adding information, in turn, encourages students to activate conceptual resources important for coherent meaning making. However, these barriers might be necessary for students in their learning process, i.e. they can only learn how to deal with them by encountering them. Learning how to deal with them in a more long-term way involves practicing and developing epistemological resources like the ones I have identified in my research: an exploratory frame, procedural self-regulation, and metacognitive reflection. This, in turn, allows for practice and progress of students' systematic engagement, which makes it possible to conceptualize barriers as productive in a situated way (Harrer, 2013).

I have previously described how students activated exemplars (e.g. the salt and ice challenge) to deal with a potential cognitive conflict when they observed a decrease in temperature when salt was added to ice. A more long-term solution is to make a habit out of testing what we do not trust. Once again, this can be done by practicing the epistemological resources mentioned earlier on: Procedural self-regulation will support the structure of a new testing cycle, and the exploratory frame (through exploratory talk) will support the continued collaborative investigation. This can be exemplified with one of the pairs of physics teacher students (V) that initially did not trust the observation ("It really gets colder […]") they made with an IR camera (the temperature decreased when salt was added to the ice): "I don't get it! […] No, okay, it gets colder and it melts faster. This makes no sense. I give up". However, instead of giving up, they chose to solve the discrepancy by designing a testing experiment. This led them to finally conclude: "But we can see that it becomes colder even when we make a slush […] So it becomes colder".

Another potential challenge is the "wow" factor or fascination that follows with tools that afford instant inquiry (perhaps related to the novelty and freedom in what to do). Chandler (2009) argues that the "wow" factor can become a problem with tools that involve dynamic visualizations if tools are used for the sake of using the tool rather than for some learning purpose. Initially, when students get to see the IR cameras, they often become fascinated with them: For example, students in V exclaimed, "Oh wow", "you are so fascinated by the IR camera" and "Those are IR cameras? Nice". It is nice that students are interested in the technology, but it might distract them from their current activity. Jordan et al. (2011) discussed the potential distraction of equipment in their research. They suggested that lab equipment should not be provided until students have planned and discussed different experimental approaches to avoid constraining their ideas. The engineering students (V) became more easily distracted (they wanted to test the IR camera for the sake of just testing it) by the provided tools than the physics teacher students. We suggested that the teacher students (V) that had previous experience with ISLE dealt with this potential barrier through their epistemological resources, i.e. their procedural self-regulation provided them with direction in the activity.

### 7.4.3 Semiotic resources support the activation of epistemological resources

In my studies, semiotic resources mediate conceptual resources and epistemological resources: The third relation in the generalized resources triangle (side c in Figure 24), between epistemological resources and semiotic resources has not been emphasized in previous research.

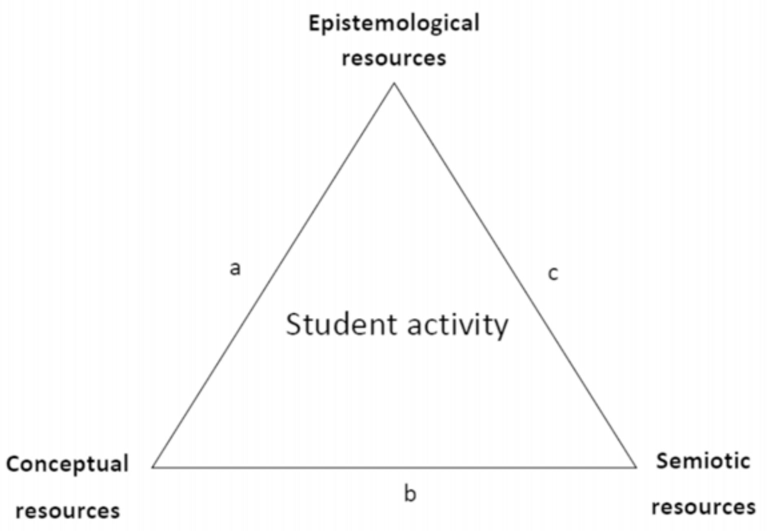


*Figure 24. The generalized resources triangle and the relations between the resources (a-c).*

There are cases of how epistemological resources relate to semiotic resources in my studies. The first and perhaps most prominent example of this, which has already been discussed in previous sections of the chapter, is the mediation of an exploratory frame through dialogue (i.e. exploratory talk). Other examples include instant inquiry (an exploratory frame mediated through the employment of semiotic resources of the IR camera) and explanatory diagrams (diagrams mediating metacognitive reflection, see Figure 26).

Another type of semiotic resource that can mediate epistemological resources is gestures. In an already presented case, metacognitive reflection is mediated through gesturing by two teacher students (V) that make meaning of freezing point depression (Figure 20) when one of the students explicitly points out that they have trouble in making meaning of the concept ("brain is on fire"). In other words, the student points out that they are aware that the conceptual resources are not forming a coherent structure yet and initiates the gesturing to mediate their current understanding of freezing point depression (which is then supported by the other student). The student is thus explicit about their trouble with organizing their knowledge. The gestures also mediate an exploratory frame.

At times during their investigation of the phenomena with the IR cameras, the teacher students (IV) tested their ideas through instant inquiry, much like how the instructors (II) (see Figure 25) moved around the material to get new observations. This testing included checking the temperature of their toes to compare with the temperature of the fingers or testing evaporative cooling by adding water to their skin. Similar to the actions and practice of the instructors, this is 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, i.e. they epistemologically frame the situation as inquiry, or in the terminology of this thesis: they activate an exploratory frame.

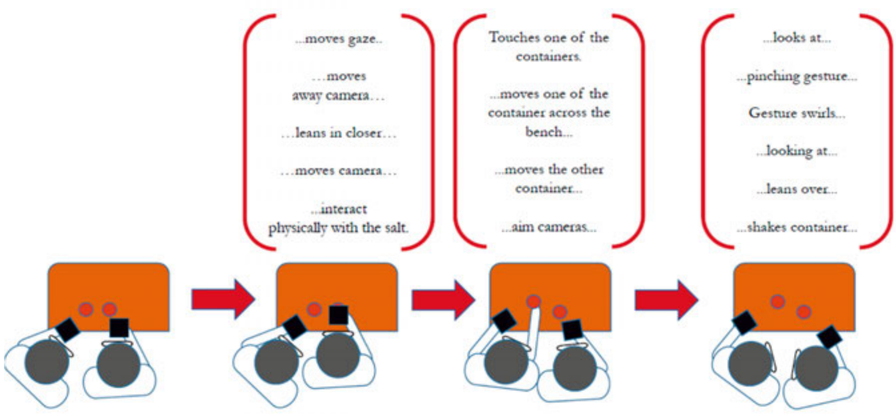


*Figure 25. Instructors (II) engaging in instant inquiry. As they discuss the phenomenon, they also move around the investigated material and move the IR cameras to get different observations and test ideas, which can be seen in the behavioral activity described above each image of the instructors.*

Another semiotic resource that mediates epistemological resources is explanatory diagrams. The physics teacher students in (V) drew diagrams to explain lines of reasoning to each other. One student did not understand the other student's reasoning about an observation (the temperature is not the same throughout the ice but different inside and on the surface). The student asked the other student to draw a diagram to explain their idea: "If you draw your own diagram. You have two ice cubes here [begins drawing]" which resulted in Figure 26. The diagram mediates metacognitive reflection.

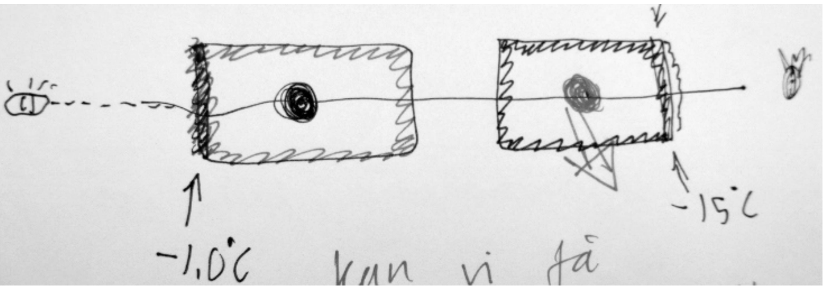


*Figure 26. An explanatory diagram was used to mediate epistemological and conceptual resources for the students to better understand each other's reasoning. The diagram depicts two ice cubes, the IR camera (the eye), and that the core of the ice has another temperature than the surface of the ice. The image is from V.*

# 8. Conclusion

The findings of the individual publications have been reexamined and discussed in relation to each other. It is now time to answer each research question and relate the answer to the teacher's practice, i.e. implications for teaching.

## 8.1 Revisiting the research questions

The purpose of the research in this thesis is to identify what resources (conceptual, epistemological, and semiotic resources) support two types of student activity in inquiry-based labs, both active and systematic engagement, and ways that students can address challenges they encounter during their activity. Let us revisit the research questions in light of the discussion and analysis of the findings in the previous chapter.

**RQ1: What resources can support students' active engagement during labs of different degrees of openness?**
Active engagement in inquiry-based labs is promoted by whatever arouses curiosity. In other words, active engagement is promoted by the  of the encountered phenomena and the recognition of one or several aspects of the same phenomena. Recognition can be achieved by comparing the phenomena with one's previous experience regarding similarities and differences (to fill the gap with relations (Wickman & Östman, 2002)). However, as previous research has shown (Dehaene, 2021; Kang et al., 2009; Kidd et al., 2012), a too-novel phenomenon can lead to frustration, and confusion and a too-recognizable phenomenon can lead to boredom or uninterest.

Several resourcest support and can be used as indicators of students' active engagement: An exploratory frame (through its instantiations like exploratory talk), exemplars, and the employment of instant inquiry tools (collections of semiotic resources) are all resources that support students' active engagement. These resources all relate to students' meaning making in my research.

Throughout the thesis, I argue that meaning making is central to active engagement. Additionally, communication is central in collaborative activities where students have to think together, i.e. active engagement in collaborative activities can be interpreted from how students communicate and interact – the semiotic resources of an activity.

Students' meaning making is made possible by them recognizing aspects of what they encounter in the learning environment. Additionally, meaning making is encouraged through novelty in what students encounter. In line with the intention of ISLE (Etkina et al., 2021) and the basis of the resources framework (Hammer, 2000; Redish, 2004) and research leading up to this framework (Clement, 1993; diSessa, 1993), teachers should identify what students are familiar with and build on that when designing labs.

An exploratory frame supports active engagement. Students become more active by thinking about the activity as a collaborative activity in which they are to investigate one or several phenomena actively. The identified instantiations of an exploratory frame (e.g. exploratory talk and exploratory gestures) can be used as indicators of active engagement.

Exemplars support active engagement. The activation of exemplars (e.g. Nosofsky, 2010; Nosofsky & Zaki, 2002) is another good indicator of meaning making, as meaning making is made possible through recognition, and exemplars are used for situational comparisons between the encountered phenomenon and previous experience. The role of exemplars has not been studied explicitly in many previous studies in physics education research.

In the research of this thesis, the activation of exemplars relates to how the lab activity is contextualized rather than the degree of openness of the labs: Exemplars were activated in the lab activities that were contextualized as physics lab activities but not in those that related to chemistry, even though labs with both types of contextualization had different degrees of openness, and all studies involved the use of IR cameras in investigating phenomena.

Tools that afford instant inquiry (Haglund, Jeppsson, et al., 2016) support active engagement. The most prominent case in my research is the IR camera which can be described in terms of several semiotic resources that all have different affordances (focus on thermal aspects afforded by the color scheme and the spatial mobility of the form of the IR camera). Additionally, instant inquiry can generate cognitive conflicts that can feed (or hinder) students' curiosity and, thus, active engagement.

Instant inquiry plays out in different ways, depending on the degree of openness of the learning environment: Students engage in dynamic practice and self-initiated talk (III) and activate exemplars (mainly IV and V) in more open learning environments (this also depends on how the lab is contextualized). In contrast, in less open learning environments, students use the cameras for confirmation and interpretation (II). Active engagement related to this affordance in less open learning environments is only relevant when students have already engaged in a more open learning environment and discovered something novel they can recognize (as in the case of the moist NaOH in II). IR cameras detect something students usually cannot perceive and transduce this into something recognizable. This allows the IR camera to generate cognitive conflicts. Students get additional easily recognizable input regarding the encountered phenomenon, which may conflict with their activated conceptual resources, such as a dark blue color appearing when salt is added to ice, indicating a temperature decrease.

I have modeled the indicators of active engagement using the generalized resources triangle (see Figure 7). Active engagement primarily involves students' conceptual and semiotic resources, as they seem not to require precise regulation or monitoring to be active. However, an exploratory frame is necessary for students to share many of the conceptual resources during active engagement. In particular, dialogue is important in mediating an exploratory frame (resulting in exploratory talk) in order to share exemplars through exploratory talk. Active engagement can be quite chaotic. For example, if you let kids play freely in a room full of toys. Additional epistemological resources are needed if the purpose of an activity is also to be systematic.

It has been argued (Robertson et al., 2019) that, aligned with the vision of NGSS, modern classroom instructions are to be guided by students' own curiosity. However, although curiosity might be important for feeding active engagement, it does necessarily lead to systematic engagement.

**RQ2: What resources can support students' systematic engagement during labs of different degrees of openness?**

Systematic engagement in labs at different degrees of openness is mainly promoted by previous experience in inquiry-based labs. In other words, systematic engagement is something that needs to be practiced over a longer period of time, preferably within labs that include problems without known answers, in order for students to develop the metacognitive skills (May & Etkina, 2002) that I describe as epistemological resources that are important for systematic engagement.

Three epistemological resources have been identified as important in supporting students' systematic engagement (as internal guidance (Kirschner et al., 2006)): An exploratory frame (through its instantiations like exploratory talk), metacognitive reflection, and procedural self-regulation.

An exploratory frame supports systematic engagement. By critically and constructively engaging with each other's arguments and monitoring the progress of the joint activity, students' exploratory talk and other instantiations of the exploratory frame help them assess and direct their activity.

Procedural self-regulation supports systematic engagement. The students keep their activity structured and directed by having an instructional approach or guiding structure to explicitly fall back to whenever the students get lost or distracted. In my research, procedural self-regulation was based on the experience of ISLE. However, it could also be based on other instructional approaches; some fit more with authentic inquiry than others (Zwickl et al., 2023).

Metacognitive reflection supports systematic engagement. Students' reflection on the nature of knowledge, how it is organized, and contextual factors like what roles or situations it relates to allows the students to assess their activity and progress. This epistemological resource should be practiced and developed in inquiry-based labs and many teacher-specific learning and development courses. The participants that activated the identified epistemological resources (an exploratory frame, metacognitive reflection, and procedural self-regulation) in inquiry-based labs to a greater degree are either students that have experience with highly open inquiry-based labs involving a guiding framework (the physics teacher students in V) or instructors with many years of research experience, i.e. the experience of authentic inquiry. In other words, both of these groups have trained on problems without known answers, which May and Etkina (2002) argue is necessary for students to develop metacognitive skills such as the identified epistemological resources. These two cohorts of teachers and teacher students have developed what Etkina et al. (2017) call productive habits for physics teachers. These epistemological resources are important not only for teachers also for being able to carry out independent investigations. They should also be practiced by physics and engineering students.

**RQ3: How can potential challenges in labs of different degrees of openness be addressed?**

There are several potential challenges that the students in my studies (and students working in labs in general) need to deal with: Disagreements, unrecognizable phenomena, and students' conceptual resources (as barriers).

Barriers can be described as cognitive resources that conflict with or inhibit other cognitive resources that are productive in a disciplinary sense (Harrer, 2013) for an activity or that distract from the current activity. Barriers include the activation of a conceptual resource that inhibits another cognitive resource, like when the ideal gas law inhibits the first law of thermodynamics for students' reasoning about the adiabatic compression of an ideal gas (Leinonen et al., 2009; Loverude et al., 2002) or "air" as a cognitive resource acting as a barrier to activation of conceptual resources related to energy conservation (C. R. Samuelsson, 2021; Wittmann et al., 2019). In addition, barriers include cognitive resources conflicting with other cognitive resources during a cognitive conflict, like when the students in my studies observed a temperature decrease which conflicted with the exemplar "salt on roads": "You can't decrease the temperature on the streets. It is not reasonable".

In contrast with the General Model of Conceptual Change (GMCC), I do not view these cognitive resources acting as barriers as inherently problematic. Even though the exemplar "salt on roads" seems problematic in the excerpt above, the exemplar is also productive before the students observe the decrease in temperature (i.e. when they observe the ice melting faster when salt is added to it). Further, it would be unreasonable to think of the ideal gas law generally as a problem or that it is a problem that students find some tools fascinating. In fact, barriers could, in a situated way (Harrer, 2013), be described as productive if they are used as opportunities to practice other cognitive resources. Barriers are an important part of the authentic inquiry that supports students in developing metacognitive skills (May & Etkina, 2002).

Students can use conceptual resources like exemplars as a shortcut in dealing with, for example, a potential cognitive conflict (this could also be viewed as avoiding the challenge completely). Another, more long-term, way of dealing with them includes metacognitive reflection, referring to one's role in relation to knowledge, in dealing with an ontological or epistemological disagreement as a challenge (e.g. instructors in II) or procedural self-regulation in order to overcome a barrier (like the physics teacher students observing a decrease in temperature in V). In general, challenges provide an opportunity to practice productive habits (Etkina et al., 2017), and an exploratory frame is an important basis for this practice. However, the results from my research suggest that less open learning environments do not promote an exploratory frame, rather the more direct the instruction is, the fewer opportunities there are for encountering challenges, i.e. opportunities to practice authentic inquiry (Zwickl et al., 2023) and metacognitive skills (May & Etkina, 2002).

## 8.2 Limitations

There are some limitations in what my work can claim. These limitations are derived from the focus of my research on students' engagement in inquiry-based lab learning environments. As such, my research has not included teacher-student interaction in this focus.

The labs are mainly qualitative because they do not involve numerical measurements used for calculations and tabulation. This could be considered a limitation for teachers who view these as essential lab experiences.

My research mainly involves undergraduate students (although one pair of instructors are included in my first study) but no students on advanced levels (of science, although some teacher students might be on advanced level in their teacher courses). Most of the content of the experiments that the students are working with in my studies are on an introductory level (although the openness in a lab activity can make the lab activity as a whole more difficult)

## 8.3 Contributions to physics education research

The research in this thesis adds to the field of physics education research by making theoretical and empirical contributions.

### 8.3.1 Theoretical contributions

- The generalized resources triangle models the relations between conceptual, epistemological and semiotic resources in students' activity.

- Instantiated resources triangles model students' activity in terms of the resources (conceptual, epistemological and semiotic) that they activate and employ.

- Both resources triangles were developed in order to describe students' activities in labs. They can also be generalized to other contexts by identifying and leveraging students' conceptual resources (e.g. through contextualization). This can be used in other forms of instruction such as lectures. Also, epistemological resources are important in other forms of instruction with a high degree of openness such as group work.

- The social semiotics and resources framework are brought together for the first time in the conceptual framework that I have developed in my thesis. By doing so, it is possible to describe both the social and cognitive aspects of students' activity. Exploratory talk, metacognitive reflection, procedural self-regulation, exemplars and instant inquiry are additional building blocks introduced to the conceptual framework to better describe students' activity. This represents a significant development for the current PER resources framework (see section 2.2.3).

- The concept of a barrier describes resources that lead to challenges during students' activity by inhibiting, distracting or being in conflict with other resources.

- IR cameras are theoretically described as tools that afford instant inquiry by identifying the affordances of the individual semiotic resources that form the collection.

### 8.3.2 Empirical contributions

- Analysis of students' reasoning and communication in lab contexts, in particular in relation to energy aspects of phase transition and calorimetry.

- Identification of resources that support students' active engagement: An exploratory frame, exemplars, instant inquiry tools (collections of semiotic resources).

- Identification of resources that support students' systematic engagement: An exploratory frame, metacognitive reflection and procedural self-regulation.

- Ways of addressing potential challenges during students' activity in inquiry-based lab learning environments.

# 9. Implications for teaching and future research

This chapter looks forward: What can teachers learn from my research? Where do I go from here in terms of future research? These are the topics for this chapter.

## 9.1 Implications for teaching

Should we design labs that are more open or less open (Hmelo-Silver et al., 2007; Kirschner et al., 2006)? Should we design labs focusing on content or lab skills (Bernhard, 2010; Holmes & Wieman, 2018)?

One way of approaching these questions is to start with what the teacher wants to achieve with the lab. In general, teachers need to be mindful of how they craft their teaching. Students' expectations (Linder & Kung, 2011) and attitudes (Wilcox & Lewandowski, 2017) are related to how teachers craft their teaching. In other words, students will frame a lab activity based on their expectations of "how it should be" in that learning context. Students can even change the results they get in a lab to what they think is the right answer (Beach, 1999).

As teachers, we should design our labs as open inquiry labs if we want our students to frame them as such and actively engage in labs (i.e. to activate an exploratory frame). If we instead want to be sure that the students carry out exactly what we want them to carry out and reduce the cognitive demand, then we should design our labs with direct instructions that keep the students' decisions to a minimum. Based on previous research, Holmes and Smith (2023) describe three ways of ensuring that students make fewer decisions on their own: By removing structure (fewer occasions for decision-making); offering choices for decisions, or; prompting students' decision-making. However, this can lead to less active or authentic engagement. As Zwickl et al. (2023) show, the two goals of traditional labs (low cognitive demand and authentic investigation) conflict with each other, and teachers have to prioritize one over the other. A solution could, in line with the recommendation of Banchi and Bell (2008), be to start in a more direct (less open) way and make the lab more open as students become more experienced with lab work. This transition could create challenges based on students' view of the nature of science and social dynamics. However, it could potentially be countered with properly trained instructors, activities that specifically train lab skills and address students' understanding of the nature of science (Doucette et al., 2018). My research shows that it is also possible to design highly open labs within a less open learning environment (as in III), i.e. a parallel learning environment to the learning environment that students are required to engage in. Having two different degrees of openness in parallel could be used as an opportunity for students that want a more challenging lab activity, perhaps because they have carried out the required lab instructions on a previous occasion or because they have developed the epistemological resources that support productive engagement in more open learning environments.

Another way of approaching the questions is, in line with the resources framework (Hammer, 2000; Hammer et al., 2004; Redish, 2004), to start with what resources students already carry with them to the lab to help them make breakthroughs in their understanding (Richards et al., 2020). My research shows that it is sometimes possible to present and contextualize the content knowledge of a discipline with "intuitive ideas" of students, e.g. exemplars, that align with what is taught. However, this can hinder the practice and development of important epistemological resources for systematicity. Students' exemplars should be identified and used to contextualize lab activities early on, which not only makes the physics more approachable but also aligns with the suggestions (Etkina et al., 2021; Redish, 2014; Robertson et al., 2019) of taking students' ideas seriously. However, students should be allowed to encounter barriers and practice their epistemological resources more long term to develop more sophisticated epistemological resources such as metacognitive reflection (May & Etkina, 2002).

A teacher can identify some common conceptual resources, discern those that align with what one wants to teach, and then adapt the teaching material according to the identified resources by contextualizing, for example, lab activities, with these resources (see Figure 27). Similar to the affective purpose of ISLE (Etkina et al., 2021), this can lead to students feeling more confident as they can relate to the activities and potentially experience coherence across tasks. Contextualizing the teaching with students' common conceptual resources fits particularly well with instructional approaches with a high degree of openness, such as ISLE. In addition, such approaches also teach a procedural structure toward which students can self-regulate. In ISLE, explanations are to build on everyday experience and intuition (Etkina, 2015) and students can be encouraged to use simple language when discussing their ideas (Etkina et al., 2021).

This might require a trade-off, as adapting activities too much to the students' conceptual resources can leave them with no barriers or open-ended problems to deal with, i.e. to practice and develop their epistemological resources (May & Etkina, 2002). Perhaps a middle ground is to start off with more adapted lab activities in the introductory education, similar to how Banchi and Bell (2008) proposed that inquiry-based activities should be more directed or closed before students have the abilities to deal with the openness of higher levels of inquiry. This leaves us with a conundrum as students need to encounter openness to practice and develop the epistemological resources that are fruitful in dealing with problems that can be encountered due to the activity not being fully adapted to the students' conceptual resources. A solution should be to keep lab activities more instructed and contextualized with students' exemplars early on but open them up as the students become more experienced with the lab practice.

I have proposed a procedure (see Figure 27) to leverage students' exemplars and other common conceptual resources in early, less open lab education (Samuelsson, 2023).

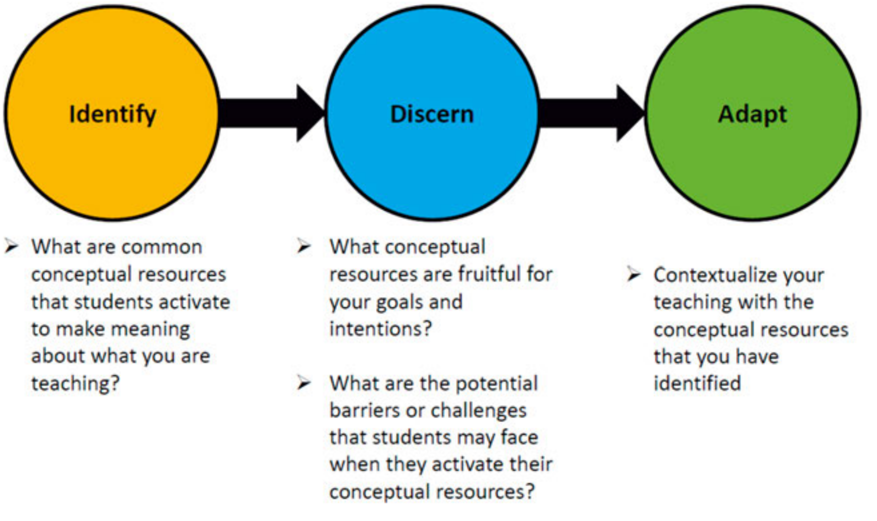


*Figure 27. Teachers can make use of students' common conceptual resources. This can be done by first identifying common conceptual resources related to the teaching content, discerning what resources are fruitful for your teaching and potential problems or barriers that the contextualization with the resources may lead to, and finally, adapting the teaching material.*

The question about the purpose of labs (Hofstein & Lunetta, 1982, 2004) has mainly been discussed in terms of lab skills versus reinforcement of conceptual knowledge (Holmes & Smith, 2023; Holmes & Wieman, 2018; Walsh et al., 2022). However, it is also important to consider the degree of openness and contextualization of labs because, as my research suggests, it will affect what type of resources students activate and employ, which in turn will affect the possibility of practicing and developing epistemological and conceptual resources that are important both for conceptual learning and lab skills.

## 9.2 Future research

I have many ideas about what I want to investigate next. I keep a list of ideas that I would like to explore more but I will just briefly present two broader ideas here (one relating to active engagement and one to systematic engagement).

My research shows that there are conceptual resources that students activate in several contexts. I would like to continue investigating the exemplars that students activate when they observe thermal phenomena and formulate hypotheses for those observations. For example, are there exemplars and/or prototypes relating to thermal phenomena that could be said to be cultural or collective (e.g. Manier & Hirst, 2008; Markowitsch, 2008) memories for particular societies? I would argue that my research suggests that "salt on (icy) roads" is an example of this.

In addition, I would also like to further explore how teachers can encourage students' active and systematic engagement in their learning processes. For example, how can teachers contextualize their teaching with students' common exemplars? The findings in this thesis suggest that some of the courses that teacher students take could play a role in students' development of epistemological resources that are important for systematicity and thus also for critical thinking.

At the time of writing this thesis, freely available large language models (LLMs, e.g. ChatGPT) have just been launched for a wider user group, and received great attention in educational research. I have just recently begun integrating the use of ChatGPT in my own teaching. I teach about cognitive science and conceptual change to upper-secondary school teacher students and the students are to critically engage with the LLM. In relation to the theme of this thesis, it would be interesting to compare students' common exemplars with those that can be provided by large language models. Additionally, it would be interesting to build on some of the ideas that Mercer and Wegerif (2001) discussed in one of their publications: How computers can assist in social symmetry, i.e. help students to reason better together by providing a tool where students can be more free and explicit in exploring their own questions collaboratively, just like in open lab learning environments. Could ChatGPT act as a tutor for students, where students run less risk of appearing as stupid in front of a teacher? This would probably require that the students have some internal guidance in order for them to be systematic. Additionally, the teacher needs to have a way of listening in or read the students' conversations with the LLM to make productive use of the students' discussions with each other and the LLM. Additionally, the teacher needs to be able to support the students in assessing the output of the LLM in case it provides the students with problematic information[38].

[38] For example, see early studies on ChatGPT 3.5 solving physics problems (e.g. Gregorcic & Pendrill, 2023)

# Sammanfattning på svenska

Den här avhandlingen fokuserar på studenters engagemang i laborativa lärandemiljöer med undersökande arbetssätt. Målet med forskningen är att utforska vad det är som gör studenter aktiva och systematiska i den här typen av lärandemiljöer.

Två teoretiska ramverk, resursramverket och socialsemiotik, används tillsammans för att beskriva hur studenter använder olika typer av resurser (konceptuella, epistemologiska och semiotiska resurser) i dessa lärandemiljöer. Ramverken har olika utgångspunkter och traditioner:

- Resursramverket utvecklades inom fysikdidaktiken av fysiker och socialsemiotiken utvecklades främst inom sociolingivstiken och multimodalitetsforskningen.

- Resursramverket tar sin utgångspunkt i studenters associationer och beteende, socialsemiotiken tar sin utgångspunkt i det sociala skapandet och tolkandet av representationer.

Det konceptuella ramverket som används i avhandlingen bygger på delar av båda dessa ramverk (resursramverket och socialsemiotik). Inom det konceptuella ramverket har en modell, den generaliserade resurstriangeln, utvecklats för att beskriva studenters aktivitet utifrån de typer av resurser som de aktiverar och använder. Med hjälp av triangeln kan studenters aktivitet karaktäriseras genom de konceptuella och epistemologiska resurser (kognitiva resurser) som studenterna aktiverar och de semiotiska resurser som de använder. Begreppet barriär har även introducerats till syntesen av de två ramverken. Barriärer är kognitiva resurser som distraherar, hämmar eller står i konflikt med andra resurser som skulle kunna leda till ett mer systematiskt och koherent engagemang.

Syftet med forskningen i avhandlingen är att identifiera de resurser (konceptuella, epistemologiska och semiotiska resurser) som stödjer studenters aktiva och systematiska engagemang samt att identifiera de sätt som studenter kan bemöta utmaningar de stöter på under sin aktivitet. Avhandlingen vägleds av tre forskningsfrågor:

1) Vilka resurser kan stödja studenters aktiva engagemang i laborationer med olika öppenhetsgrad?

2) Vilka resurser kan stödja studenters systematiska engagemang i laborationer med olika öppenhetsgrad?

3) Hur kan potentiella utmaningar i laborationer med olika öppenhetsgrad bemötas?

Som sammanläggningsavhandling utgörs en stor del av avhandlingen av mina fem publikationer: Fyra empiriska artiklar och ett bokkapitel. I avhandlingen presenteras dessa som publikation I-V.Det är dessa som utgör grunden för svaren på forskningsfrågorna. Den första publikation (I) är ett bokkapitel som bygger på den översikt om användande av värmekameror i undervisning som jag skrev i min licentiatavhandling. Övriga publikationer (II-V) bygger på videoobservation av universitetsstudenters engagemang i laborativa lärandemiljöer, och kan sammanfattas med följande:

II) Under en kurslaboration i kalorimetri upptäckte två ingenjörsstudenter ett fenomen (natriumhydroxid i pellets som ser klibbigt ut) som de uppmärksammade forskaren på. De formulerde ett antal hypoteser för fenomenet. I slutet av laborationen fick studenterna tillgång till värmekameror för att observera sin upptäckt på ett nytt sätt. Studenterna kunde snabbt bekräfta en av sina hypoteser med värmekameran men var inte längre lika dynamiska, eller utforskande i sin kommunikation, som de var när de formulerade hypoteserna. Två labinstruktörer fick utföra samma experiment med värmekamerorna och visade sig vara mer dynamiska, och utforskande i sin kommunikation, än studenterna.

III) Under en kurslaboration i kalorimetri fick två par ingenjörsstudenter tillgång till värmekameror som de fritt fick använda under sitt arbete med kurslaborationen. Två andra par ingenjörsstudenter deltog också i studien men utan att få tillgång till värmekameror under kurslaborationen. Studenterna med värmekameror initierade resonemang oftare på egen hand än studenterna utan värmekameror, de var även mer kontinuerliga i sin praktik än studenterna än värmekameror och fokuserade nästan helt uteslutande på makroskopiska aspekter i sina resonemang. Alla studentpar fick sedan tillgång till värmekameror för att studera liknande fenomen som de arbetat med under kurslaborationen (men mer anpassat för undersökning med värmekameror). I den här laborationen initierade alla studenter resonemang på egen hand i lägre grad (de svarade mest på frågor från forskaren), men studenterna som hade haft värmekameror tidigare var fortsatt kontinuerliga i sin praktik och det gällde även ett av paren som tidigare inte haft värmekameror. Alla studenter fokuserade även på makroskopiska aspekter i sina resonemang.

IV) I den här studien deltog grundlärarstudenter i en designad lärandesekvens (i tre delar, A-C) som fokuserade på att koppla varje delexperiment (som involverade värmekameror) till studenternas tidigare erfarenheter från vardagen. Lärandesekvensen anordnades i samband med en kursmodul om fysik för grundlärarstudenter och handlade om fasövergångar. I sina diskussioner kontextualiserade studenterna, utifrån avdunstning, del A med vardagssituationen för del B (innan de visste något del B) och del B med vardagssituationen för del C (innan de visste något om del C). De avslutade del C med att återvända till situationerna i A och B. På så sätt skapade studenterna koherens kring avdunstningsbegreppet.

V) I den här studien deltog tre ingenjörsstudentpar och tre fysiklärarstudentpar i en öppen undersökningsbaserad labb (baserad på the Investigative Science Learning Environment, ISLE) där de behövde ta många egna beslut. Lärarstudenterna hade redan innan studien erfarenhet av liknande undervisning. Alla studenter var aktiva under laborationen men lärarstudenterna visade sig vara mer systematiska i sitt arbete än ingenjörsstudenterna. Det var tydligt att de hade en struktur för procedur att luta sig mot samt att de resonerande om kunskap på ett annat sätt än ingenjörsstudenterna (lärarstudenterna pratade om kunskap på en metanivå och utvärderade sig själva).

Tillsammans med publikationerna visar avhandlingen att studenters aktiva engagemang i laborationer relaterar till dels hur nytt ett fenomen är och dels hur väl studenterna känner igen fenomenet. Flera resurser identifieras som stödjer studenters aktiva engagemang, främst konceptuella och semiotiska resurser (tillsammans med att studenterna tänker på lärandemiljön som utforskande, en så kallad utforskande ram som epistemologisk resurs). Det finns några typer av resurser som kan användas som indikatorer på aktivt engagemang: Konceptuella resurser såsom exemplar, epistemologiska resurser såsom en utforskande ram (genom till exempel utforskande tal) och användande av verktyg som erbjuder omedelbara undersökningar (till exempel värmekameror). I avhandlingen argumenteras det även för att studenters egen systematik vid undersökande arbetssätt i laborationer grundas i deras epistemologiska resurser. Tre epistemologiska resurser identifieras som stödjer ett systematiskt engagemang: En utforskande ram, metakognitiv reflektion och procedurell självreglering (mot någon typ av undersökande arbetssätt). Dessa resurser utvecklas och tränas främst genom att delta i undervisningsaktiviteter som baseras på ett undersökande arbetssätt men potentiellt även genom undervisning som behandlar lärande och utveckling (såsom kurser som ingår i lärarutbildningen).

Avhandlingen inkluderar även en diskussion om hur olika resurser kan användas för att bemöta olika typer av potentiella utmaningar som studenter kan stöta på i arbetet med laborationer som bygger på ett undersökande arbetssätt: Konceptuella resurser kan användas som kortsiktiga lösningar men en mer långsiktig lösning involverar aktivering av epistemologiska resurser. Avhandlingen avslutas med att relatera resultatet till lärares praktik, det vill säga forskningens betydelse för undervisningen.

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# Appendix A – Consent forms for II-V

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:________________________________

UPPSALA
UNIVERSITET

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Jesper Haglund, Institutionen för ingenjörsvetenskap och fysik, Karlstad universitet
Maja Elmgren och Felix Ho, Institutionen för kemi – Ångström, Uppsala universitet

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Jag ger mitt medgivande till deltagande i den vetenskapliga studien.

Underskrift:_______________________________________

Namnförtydligande:_______________________________

UPPSALA UNIVERSITET

## Medgivande för studie kring användning av värmekameror som pedagogiskt hjälpmedel (Lärande och undervisning i termodynamik)

Studiens syfte och vad deltagandet innebär:

Som en del i den pedagogiska utvecklingen av laborationer i kurser i fysik vill vi genomföra en forskningsstudie kring hur man kan använda värmekameror, och vad de bidrar med, vid öppna laborationer och lärandesekvenser 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.

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 studien är helt frivilligt. Du kan när som helst under, eller efter, studien 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 lärandesekvensen.
- ☐ Jag tillåter endast de som omnämnts i informationsbladet att ta del av insamlad video- och ljuddata.
- ☐ Jag förstår att publicerad data ej kommer att kunna användas för att identifiera mig.
- ☐ Jag har förstått att jag när som helst kan dra mig ur studien och att rådata som inkluderar mig då kommer att förstöras.

**Jag ger mitt medgivande till deltagande i den vetenskapliga studien.**

Underskrift:________________________________________

Namnförtydligande:___________________________________

Mail: ________________________________________________

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

UPPSALA UNIVERSITET

UPPSALA UNIVERSITY PER

## Medgivande för studie inom projektet "Lärande och undervisning i termodynamik"

Studiens syfte och vad deltagandet innebär:

Som en del av ett forskningsprojekt om lärande och undervisning i termodynamik vill vi genomföra en forskningsstudie kring resonerande i termodynamiklaborationer som involverar fasövergång.

Syftet med studien är att undersöka studenters resonemang, praktik och kommunikation under labarbete som involverar fasövergång samt vad studenter uppmärksammar under arbetet, särskilt i samband med stöd av tekniska hjälpmedel. Data kommer att samlas in genom videoinspelning (bild och audio) av det laborativa arbetet samt enkäter.

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, bild och andra personliga detaljer kommer aldrig att nämnas i något sammanhang utanför forskarnas arbete med datan.

Deltagande i studien är helt frivilligt. Du kan när som helst under, eller efter, studien 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 enkät-, video- och ljuddata samlas in under mitt deltagande i lärandeaktiviteten.
- ☐ Jag tillåter endast de som omnämnts i informationsbladet att ta del av insamlad video- och ljuddata.
- ☐ Jag förstår att publicerad data ej kommer att kunna användas för att identifiera mig.
- ☐ Jag har förstått att jag när som helst kan dra mig ur studien och att rådata som inkluderar mig då kommer att förstöras.

**Jag ger mitt medgivande till deltagande i den vetenskapliga studien.**

Underskrift:_______________________________________

Namnförtydligande:_______________________________

Mail: ______________________________________________

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

# Appendix B – Example of transcript (II)

| Transcriptionline | Time stamp | Interlocutor | Swedish speech | Translated speech | Body | Interaction with artefacts | Gaze | Comment |
|---|---|---|---|---|---|---|---|---|
| 3 | | PhD 2 | Jag tror att vi behöver ny natriumhydroxid. Den här går ju inte att skopa. | I think we need some new sodium hydroxide, this here you can not scoop. | | | Blickarna riktade mot NaOH | Doktoranderna hade oftast blicken bredvid displayen snarare än direkt mot displayen och tittade då mot själva experiementet istället. Blickarna förändrades mot displayen då de förklarar aspekter från kameran. |
| 4 | | PhD 1 | Jag tror att vi har det här. | I think we got it here. | | Lyfter och skakar en sluten behållare med natriumhydroxid | | |

# Appendix C – Example of initial and final transcript (III)

| Transcriptionline | Interlocutor | Swedish speech | A exo/endo | B trans heat | C Lab practice | D Spatial | E Calc/det | F Spont/ent | G Symbolic | H Errors | Summary |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 | S2 | Det var väl att eh kolla på eh...upplösningsentalpierna. | | | | | | | | | "Kolla på" upplösningsentalpier |
| 32 | S1 | Ja, det...lab inom liksom termokemi. Eh så det är bättre...men man har också såhär kanske vissa energi...eller reaktioner kan ske spontant även om de är endoterma, kanske lite koppling till entropi och så. | | | | | | | | | Termokemi-lab. Att endoterma reaktioner kan ske spontant. Koppling till entropi [?]. |

| Student | Speech | Reasoning |
|---|---|---|
| S2 | Det var nästan samma utöver att kameran visade decimalt och det var lite svårare att se på termometern. | **1 (IR camera and thermometer showed almost the same result)** |
| S2 | Nu är problemet hur vi ska sticka hålet där. | **5 ((How to make a hole through the foil : pencil ~ not pencil -> use thermometer) & starts magnetic stirrer)** |
| S1 | [visar penna] | |
| S2 | Nej, jag tror inte att vi borde ta en penna. Men om vi gör såhär...kan du hålla? Nu har vi tappat [ohörbart] här | |
| S2 | Det räcker med en [folie] | |
| S1 | Ta bara den här [pekar på foliebit]. | |
| S2 | Om vi gör såhär | |
| S2 | Den...här [sätter i termometer i folie] | |
| S2 | Så sätter vi in den här [ansluter magnetomrörare] | |

# Appendix D – Example of transcript (IV)

Excerpt from transcripts

-------Bastu, förutsägelse------------

Forskare: Så första fenomenet kallas för bastu. Så vad är det för någiot som händer som har med värmelära att göra i bastun? Om man sitter i bastu...här är själva situationen: om man sitter i en bastu och någon häller en större mängd vatten på stenarna i bastun. Hur känns det? Och varför känns det så?
Så om ni tar och diskuterar det.

1För det första så förångas vattnet då det hamnar på stenarna och värmen stiger.

3Hur känns det?

1Ja, nu. Det känns varmt.

2Ja fast det tar en stund. Först är det såhär tschhh och sen så kommer ångan så öhhhff...[smärta]

5Men det är väl för att vattnet, tar dess termiska energi och sen när det kommer i kontakt med vår kropp, vår hud....

# Appendix E – Example of initial summary and transcript (V)

| Grupp 5 (Lär) V:17-20 | | |
|---|---|---|
| **Epistemic games/resources** | **Struktur** | **Struktur (forts.)** |
| **Exemplar för rationalisera obs:** Salt på vägar V1704:55, Koka pasta V1705:43, isberg i saltvatten – saltvattnet är mycket kallare än isberget V1801:55, salt and ice challenge [tänker rätt men drar fel slutsats]V1900:30<br><br>**Exemplar för rationalisera hyp.**: Salt på vägar, rost på bilar, luckra upp V1810:50<br><br>**Express Knowledge**:<br><br>"så tänker du" V1708:07, "Det är det du menar. Om det är det du tänker." V1708:25, "tänker fräta. Vi tänker att.." V1709:06, "hänger du med på vad jag försöker säga? Det var rörigt" V1714:36, "Du kanske har rätt men jag tänker" V1718:35, "jag fastnar kanske för mycket, säg till mig" V1719:42, olika uppfattning om en hypotes (diskuteras) V1808:10, "det är vad du vill säga" V1810:03, "du menar att vi har olika mängd? Ja jag tänker..." V1813:20, ena studenten övertygar andra om värmekameran ger rätt obs. V1821:44, "du har rätt.jag kanske tänker dumt" V1828:58, "det har jag svårt att se" V1910:05, "beskriver scenario, påstår du att.." V1912:28, "bra! | **Obs**: O1:Knastrar<br><br>O2: Isen är blöt. Den smälter fortare.<br><br>O3: Isbiten blir "lös", det blir blött runt omkring.<br><br>**[Recognition/intuition]**: I1: Salt på vägar<br><br>I2: Koka pasta<br><br>**Hyp**: H1(O2): Saltet är varmt och värmer upp isen.<br><br>H2(O2) Smältpunkten blir vid en lägre temperatur. Saltet löser sig i isen och ger vattnet lägre fryspunkt.<br><br>H3(O2): Salt luckrar upp saker (även t.ex. bullar)<br><br>**Exp (utan utrustning V1710:30)**:<br><br>E1(H1): Lägga salt i frys s.a. salt och is har samma T från början. Häll på salt på is. (**P**. Isen smälter inte )<br><br>E2(H2): Hitta ny fryspunkt. Is fryser vid 0 grader (vid atmosfäriskt tryck). Rum vid 0 grader (mod. -1 grad), häll på salt på is. (**P**. Isen smälter)<br><br>E3(H2): Saltlösning i -1 grad. Kontrollera om det fryser eller inte. Om det inte fryser, fortsätt med | E8(O4): häller vatten på en isbit och sen salt på det.<br><br>U6(E8): Kontrollera med värmekamera → lägre T<br><br>E9(O4): Salt på is. Kontrollera T.<br><br>U7(E9): Med värmekamera ser de att det blir -15 grader. → O5: Känner på isbiten, det känns kallt<br><br>H4(O5): Isens värmledningsförmåga ändras när det hälls på salt.<br><br>H5(O3): energi krävs för smältningen, krävs snabbare när salt är på isen. Leder till lägre T.<br><br>E10(H5): Testa om omgivningen i en adibatisk miljö får lägre T då salt hälls på is än om endast is är i kalorimetern.<br><br>U8(E10): Is i kalorimeter. Kontrollera in med värmekamera mot vägg på insida. Häller i rums-T vatten för att få ny ref.temp (behövs ju egentligen inte). Ut med vatten, i med ny is och salt. (**P**. T blir lägre) → T blir lägre → stödjer H5<br><br>H6(O4): T blir bara lägre på utsidan av isbiten (vatten och salt som får lägre T, inte isens kärna) |

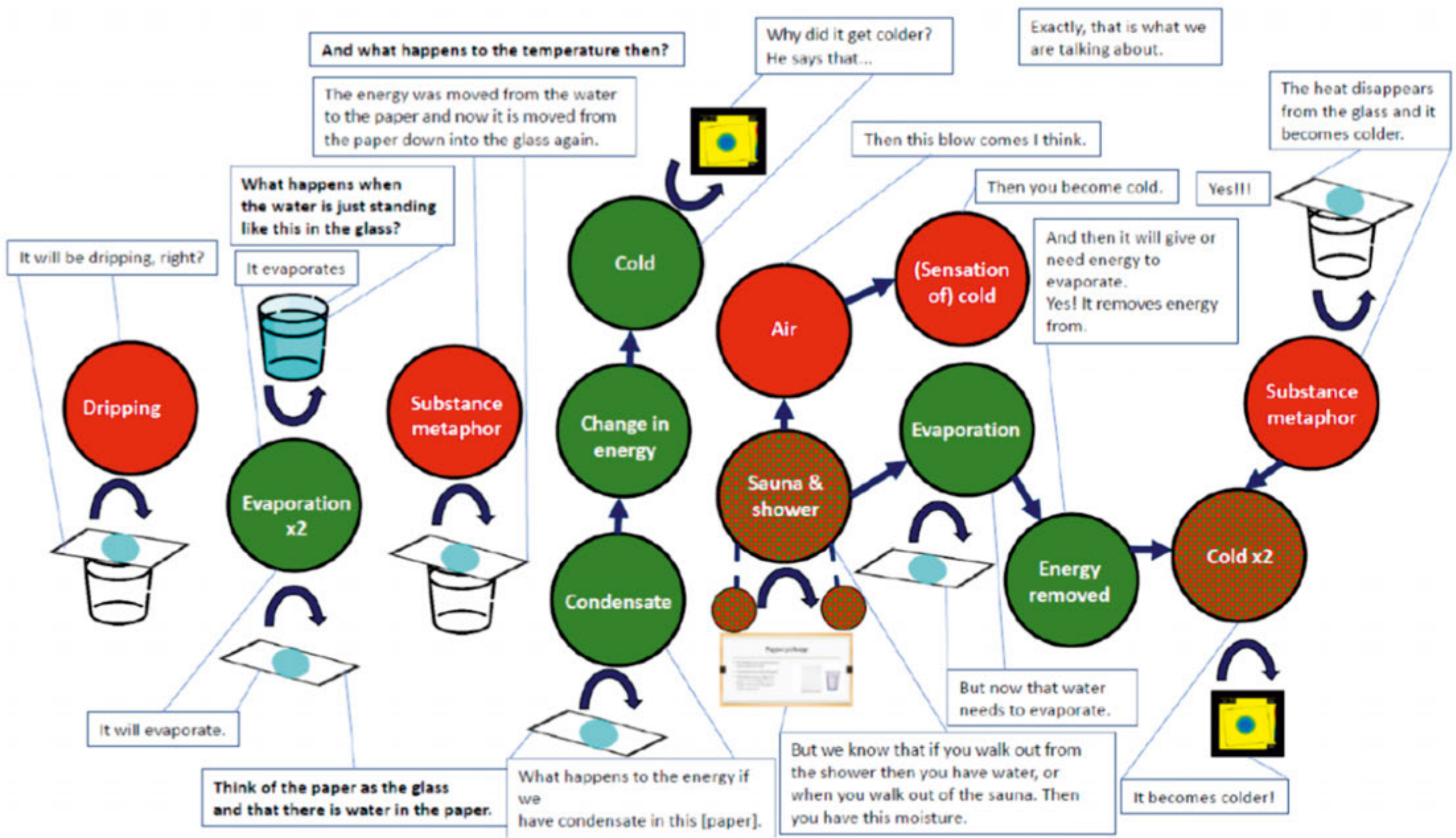
| Deltagare | Tal | Kategori 1 | Kategori 2 |
| --- | --- | --- | --- |
| S2 | Ja och så gör vi samma sak här | | |
| S1 | Vad betyder det? | | |
| S2 | Det här vattnet kommer vara kallare om min hypotes är rätt. | Selfreg | |
| S1 | Det är det! Men jag fattar inte vad du menar, kan du berätta igen? | Limitiation of knowledge | |
| S2 | Att det här vattnet är salt. Alltså okej såhär: när du mäter nu så är det inte isens temperatur du tittar på lika mycket som vattnets temperatur. Och det här vattnet kan inte bli mycket mer under 0 grader för då kommer det att vara is. Så därför kan inte det här vattnet vara mer än eller mindre än -1.5, men det här vattnet kan komma ned långt under 0 grader för att det är vatt...saltblandat nu | | Exploratory talk |
| S1 | För att vi sänkte fryspunkten | | |

# Appendix F – Table structuring data (I)

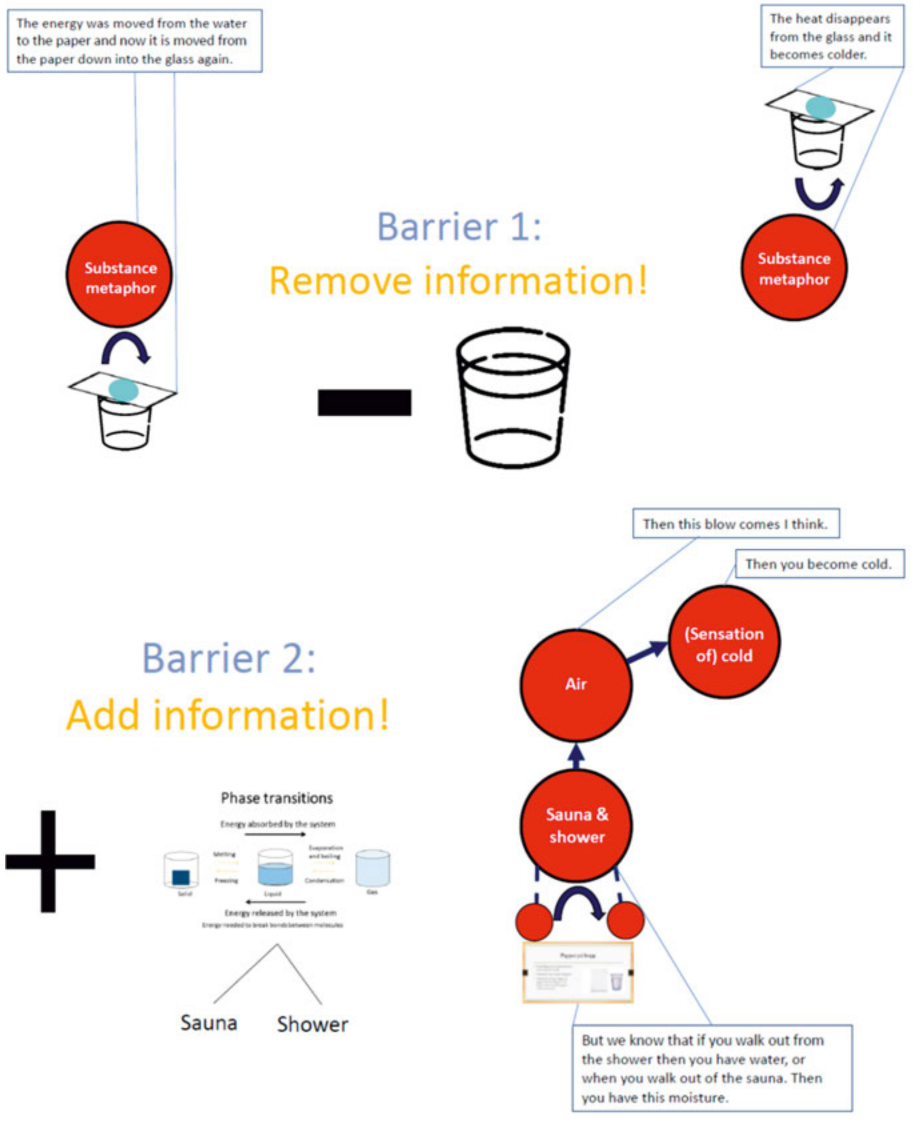
| Title | Authors | Year | Journal/proc. Title/book title | Intended education level | Content & activities | Data | Summary | Keywords, type | Keywords, theory | Keywords, methodology |
|---|---|---|---|---|---|---|---|---|---|---|
| **Hot vision: Affordances of infrared cameras in investigating thermal phenomena** | Samuelsson, Elmgren & Haglund | 2019 | Designs for Learning | University | **Deliquescence and heat transfer**: Sodium hydroxide exposed to surrounding air in a lab | Uni. engineering students and instructors in chemistry | Two engineering students and a pair of instructors investigated some sodium hydroxide reacting with water from the surrounding air. Results showed that the students mainly used a cumulative type of talk and static posture when working with the IR cameras (but exploratory before using the cameras) and the instructors used exploratory talk in addition to a more dynamic investigation (moving IR cameras, testing things etc.). The IR camera seem to have both disciplinary and pedagogical affordance as both the members of the discipline (the instructors) and the students used the cameras in a meaningful way to discuss the phenomenon and draw conclusions: the instructors gained a deeper understanding of the phenomenon by challenging each others explanations and the students immediately associated red to warmness which led them to a final explanation. | Chemistry, authentic, empirical, university | Disciplinary affordance, pedagogical affordance, typology of talk, semiotic resource, multimodality (body and posture) | POE, video, transcription, qualitative, multimodal conversation analysis, field notes |
| **Pupils' early explorations of thermoimaging to interpret heat and temperature** | Schönborn, Haglund & Xie | 2014 | Journal of Baltic Science Education | Elementary school | **Heat and temperature:** Authentic contexts. POE on thermal conductivity of wooden, metal and woollen object, interpretation of static thermal images, measurement with thermometer | Students in 7th grade | Initially, the students thought of sense of touch as a good thermometer. The students did not take the full use of the resources offered by the cameras, they were instead used as thermometers. Observations with IR cameras lead to a cognitive conflict that the students could not resolve. It is suggested that students of this education level are introduced to a simple model of heat flow before they use IR cameras and that they get to work with an easier task. | Physics, authentic, elementary, empirical | Cognitive conflict, productive resources, multimodality (touch and vision), misconceptions | POE, video, transcription, qualitative |
| **Students' framing of laboratory exercises using infrared cameras** | Haglund, Jeppsson, Hedberg & Schönborn | 2015 | Physical Review Special Topics - Physics Education Research | Upper secondary school | **Friction and dissipation, conservation of energy, temperature and thermal conductivity of different materials:** Eraser against table, feet against floor, dropping steel ball onto asphalt, temperature of a piece of wood, metal knife and woollen beanie, hot water poured into a ceramic mug and a thin plastic cup. | Technology students in 11th grade | Investigation of the disciplinary affordance of IR cameras and students' framing. The students were given a short description on how the IR cameras work. The students then participated in four activities: Friction and visualization of dissipation, conservation of energy, objects of different materials at room temperature and hot water being poured into containers of different materials. Results show that the students conceptually framed the activities in similar ways (they ignored heat conduction at the station involving friction and approached the activity with a steel ball from a macroscopic perspective) but that the epistemological framing differed between the participants: One student wanted to strictly follow instructions and another looked for examples that deviated from the instructions. The IR cameras invited to instant inquiry. The students continued framing sense of touch as a good measurement of temperature. The IR cameras have a disciplinary affordance related to macroscopic concepts in thermodynamics (but not to microscopic such as particle interaction). | Physics, high school, empirical | Disicplinary affordance, conceptual framing, epistemological framing, instant inquiry | POE, video, transcription, qualitative |

# Appendix G – Barriers in students' reasoning

Students' reasoning as presented at the Nordic Physics Days 2021. The analysis was based on the data for Publication IV. Red nodes indicate barriers and green nodes indicate productive resources for the activity. Images outside of the nodes are the attended objects (semiotic resources) and arrows show the associations. Transcripts are included in the boxes.



Two ways of redesigning the teaching sequence, were proposed in the presentation, to make it more accessible for students: Removing or adding information from/to the learning environment.



# Acta Universitatis Upsaliensis

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