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Understanding meaning-making in physics education through semiotic resources

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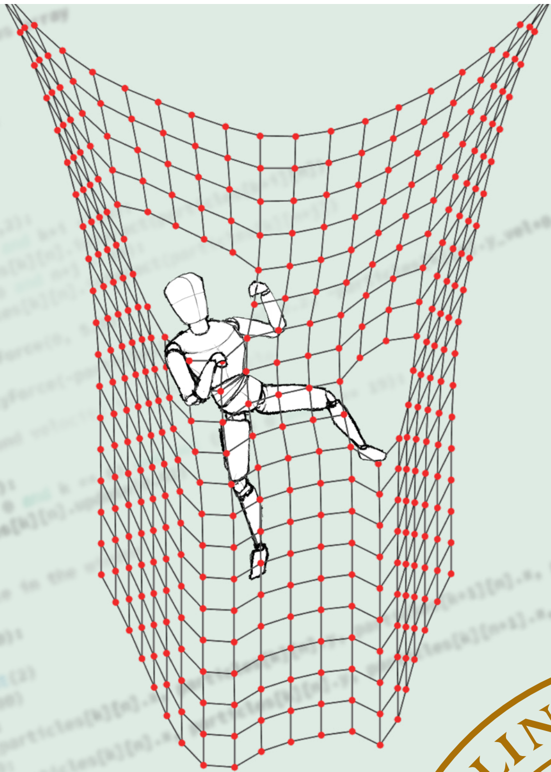

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Understanding meaning-making in physics education through semiotic resources

by Kim Svensson

DOCTORAL DISSERTATION

Thesis advisors: Assoc. Prof. Urban Eriksson, Prof. Ann-Marie Pendrill

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Linking Programming to Representations: Understanding meaning-making in physics education through semiotic resources

Abstract

As a student learns physics, they must discern, explore and understand different physical concepts. The concepts are represented in different ways, such as formulas, graphs, images, animations, and each different representation provides access to another facet of the full concept. The research presented in this thesis attempts to better understand and describe the student's usage of these representations, especially in a programming context.

The first project studies students as they construct models, implement them, and visualise them using Python and the Processing IDE. A group of upper secondary education pupils volunteered to participate in a five part workshop in which they implemented different models of physical systems, such as springs and heat diffusion. The analysis of the data was done using the lens of Social Semiotics and Variation Theory of Learning. The frameworks guided the description and interpretation of observed phenomena. The concept of Transductive Link was defined and explored with respect to physics education research and programming was identified as a potent transductive link to help the movement from an abstract mathematical model of a phenomenon to an interactive visualisation of the phenomenon.

The second project focused on exploring social semiotics and variation theory of learning to obtain a better understanding of how to construct new representations for use in physics education. Qualitative data in the form of audio and video was recorded using Zoom™ as first year physics students constructed their own representations, as well as interacting with a, to them, new representation of thermal energy. The data collection was done remotely because of the Covid-19 pandemic. The analysis for this project is not complete, but two papers have emerged that uses the same data. The first introduces the concepts of active and passive transductions to better describe how students perform transductions. The second compares the theoretical frameworks of social semiotics and the theory of registers of semiotic representations to study how, and if, the frameworks may be used together to better describe learning situations in physics education. Both frameworks may be used together when analysing data and their results may also be compared to each other.

A side-project focuses on an attempt to model ideas from social semiotics using a mathematical model to obtain a better understanding of the dynamics of semiotic resources.

Key words

Physics Education Research, Social Semiotics, Variation Theory, Affordance, Multimodality, Programming, Meaning-Making, Transduction, Semiotic Resources

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Cover illustration front: Illustration and composition by Kim Svensson. The image depicts a person interacting with a visualisation produced by code.

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Everything should be made as simple as possible, but not simpler
— Albert Einstein

Contents

List of papers

The ideas presented in this thesis are based on the following publications.

I **Svensson, K.**, Eriksson, U., Pendrill, A.-M., and Ouattara, L. (2020). Programming as a semiotic system to support physics students' construction of meaning: A pilot study. *Journal of Physics: Conference Series*, 1512(1):1–12.

II **Svensson, K.**, Eriksson, U., and Pendrill, A.-M. (2020). Programming and its affordances for physics education: A social semiotic and variation theory approach to learning physics. *Physical Review Physics Education Research*, 16(1):1–15.

III **Svensson, K.** and Eriksson, U. (2020). Concept of a transductive link. *Physical Review Physics Education Research*, 16(2):26101.

IV **Svensson, K.**, Lundqvist, J., Campos, E., and Eriksson, U. (2021). Active and passive transductions – definitions and implications for learning. *European Journal Physics,* 43 025705.

V **Svensson, K.**, Campos. E. (202X) How do students use representations in physics? A comparison of two semiotic perspectives *Physical Review Physics Education Research* – submitted

VI **Svensson, K.** (202X) Constructing representations based on Social Semiotics and Variation Theory – draft

VII **Svensson, K.**, Eriksson, U., Linder C., and Clark, J. (202X) Dynamics of semiotic resources *Physical Review Physics Education Research* – submitted

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I wish to thank Vattenhallen Science Centre at Lund University for their interest in my research and for allowing me to use their resources for the first study.

I also want thank my family and all my friends that have supported me as I tried to explain my research to them. I especially thank my partner, Helen Edström, that has been forced to listen to every presentation and to read every paper. Without the support of my friends and family, the PhD would have been a lot harder to go through, especially with respect to writing this thesis.

I thank all the willing participants that donated their time and thoughts to all the projects, without you the research would literally not be possible.

Popular summary in English

The ideas presented in this thesis are very much tied to the framework of *Social Semiotics* and describe the activities, tools, and representations that are used to make meaning about concepts in physics. Formulas, graphs, animations, laboratory equipment, bouncing on a trampoline are all examples of *semiotic resources* that are used in some manner to investigate, explore, manipulate, and communicate meaning in physics.

Programming as a tool for meaning-making in physics education was examined using the lens of social semiotics and identified as a potentially potent tool to better understand different physical concepts. The mathematical formalism of the physics discipline makes creating code representations of different formulas straight forward. However, in the process of creating a code representation of a mathematical formula, the student must unpack the different parts of the formula. The student must, for example, find a way to represent matrices or vectors if they wish to simulate quantum mechanical systems. This unpacking of the different aspects of a formula provides the student access to the underlying ideas of the formula and to produce a functioning simulation, they must accurately construct a code-representation of the formula.

The second part of programming is the output and this project has focused on animations and interactive visualisations as the output from the program. The student's must choose how, and what, they choose to represent in the output. This provides a researcher, but also an instructor, insight into the student's *relevance structure*. The student's relevance structure captures what the student finds relevant for the situation. For example, a student may not find the magnitude of a force relevant in understanding a mechanics problem, but in reality, it is very relevant to be able to come to a correct conclusion about the situation. By using the student's relevance structure, interventions may be developed and deployed that addresses the specific errors in student understanding.

The full package of programming involves creating a model to implement, a code-representation of the model, and a visualisation of it. However, this is not a one-way street; the student may, and should, move between the different *semiotic systems* that each provide access to a specific facet of the physical concept they intend to implement. The student may enter into a feedback loop where they may explore and manipulate their model in such a way to provide new insights. By varying values, adding terms, changing visualisations, adapting the model, the student has the ability to build their own understanding of the phenomenon in question. When they have obtained an understanding of the phenomenon through constructing their own model, their own simulation, and their own visualisation, it should be compared with the physics discipline's own way of describing, and representing, the phenomenon.

To better understand how students use and create their own representations, constructs had to be developed for the social semiotics framework. They were *transductive links*, *transductive chains*, and *active* and *passive* transductions. Transductions describe the movement from a semiotic system to another, such as moving from a formula to a graph, or from code to visualisation. Programming was identified as a transductive link between mathematical formula and animation. A transductive link helps to facilitate the transduction and a good transductive link will help students perform, or follow along, the transduction. An instructor that uses speech and gestures to help connect a formula to a graph, are using speech and gestures as transductive links.

Active and passive transductions attempt to describe how students perform a transduction and if an observer can gain some information about their disciplinary discernment, or understanding, of the concept in question from the transduction. If the transduction is active, some information may be obtained with regards to the student's understanding of the underlying concept, but if the transduction is observed to be passive, no information can be obtained with regards to the student's understanding. Active and passive transductions are defined using a concept called *shown engagement* which in turn captures the idea that students should engage with the concept in one of the following ways; they should unpack it; or they should filter out aspects; or they should highlight aspects.

To further understand how students use representations, a comparison between social semiotics and the theory of registers of semiotic representations was done. Both frameworks use the ideas of semiotics and the construction of signs to mediate meaning, as central parts of their constructs. Both frameworks have identified the same aspects of using representations to learn as relevant and the conclusion from the study is that results both frameworks may be compared with each other and that they may also be used together to obtain a better description of a learning situation in physics education.

Another approach to understanding, specifically, semiotic resources comes in the form of the construction of a mathematical model of the concept. The aim of the model was to find a way to better compare two semiotic resources, such as a text and an image, with each other from a meaning-making perspective. The model uses a dual-space framework to model semiotic resources as a sum of discernible aspects. By using the notion of discernible aspects, two semiotic resources may be compared to each other, even if they appear to be extremely different, such as a gesture and a movie. By introducing operators to the model, changes and modifications to semiotic resources may be modelled and the order of operators are identified as being important. This observation is based on the observed phenomenon of flipped classroom where the student is tasked to read the material before going to the lecture, a teaching form that has proven itself to produce better results compared to the reverse situation.

The learning situation is modelled as a large number of discernible aspects grouped into different semiotic resources. The student's focus moves between the discernible aspects the student finds relevant. The student's relevance structure is found by examining which discernible aspects they converge towards. As stated above, the student's relevance structure may now be used to implement interventions that help them discern new discernible aspects, or make them realise that some discernible aspects are relevant for the problem itself.

In essence, this thesis examines student's usage of semiotic resources in physics education and attempts to describe the role of semiotic resources using different theoretical approaches.

Populärvetenskaplig sammanfattning

Idéerna som presenteras i denna avhandling är starkt kopplade till det teoretiska ramverket *Social Semiotik* och beskriver aktiviteter, verktyg, och representationer som används i skapandet av mening i fysik. Formler, grafer, animationer, laborationsutrustning, hoppa på en trampolin är alla exempel av *semiotiska resurser* som används för att undersöka, utforska, manipulera, och kommunicera mening i fysik.

Programmering, som ett verktyg för meningsskapande i fysikundervisning, undersöktes med en socialsemotisk lins och identifierades som ett användbart verktyg för att bättre förstå olika fysikaliska koncept. Den matematiska formalismen som fysikdisciplinen använder gör att det är okomplicerat att skapa kodrepresentationer av olika fysikaliska formler. Men i skapandet av kodrepresentationen av en formel måste studenten packa upp de olika delarna av formeln. Student måste, exempelvis, hitta sätt att representera matriser och vektorer om de ska simulera ett kvantmekaniskt system. Detta uppackande av olika aspekter erbjuder studenten tillgång till de underliggande idéerna av den fyskaliska formeln och för att producera en fungerande simulering, måste studenten konstruera en korrekt kodrepresentation av formeln.

En annan del av programming är dess produkt, och detta projekt har fokuserat på animationer och interaktiv visualisering som produkten av programmet. Studenten måste välja hur, och vad, som representeras i visualiseringen. Vad studenten väljer att visualisera ger insikt in i studentens *relevansstruktur*. Studentens relevansstruktur fångar vad studenten tycker är relevant för situation. Till exemepel, en student kanske inte finner storleken på en kraft relevant i ett mekanikproblem, men i verkligheten så är storleken på kraften väldigt relevant för att komma till rätt slutsats. Genom att använda studentens relevansstruktur kan nya internvetioner skapas och appliceras så att de addresserar fel i studentens förståelse.

Totalt sett så involverar programmering skapandet av abstrakta modeller för ett fysikaliskt koncept, implementationen av modellen och visualiseringen av modellen. Men denna process går åt båda hållen; studenten bör röra sig mellan de olika *semiotiska systemen*, som erbjuder tillgång till olika bitar av konceptet studenten har implementerat. Studenten kan hamna i en feedback-loop där de rör sig mellan matematisk model, kodrepresentation och visualiseringen för att manipulera och undersöka olika bitar av konceptet. Genom att variera värden, lägga till termer, ändra i visualiseringen, kan studenten bygga en egen förståelse av konceptet. När studenten har skapat sin egen förståelse ska den jämföras med fysikdisciplinens sätt att beskriva och representera konceptet.

För att bättre förstå hur studenter använder och skapar egna representationer skapades flera nya teoretiska konstruktioner för det social semiotiska ramverket. De var *transduktiv länk*, *transduktiv kedja*, *aktiva* och *passiva* transduktioner. Transduktioner beskriver rörelsen mellan olika semiotiska system. Förflyttningen från formel till graf, eller från kod till visualisering, är exempel på transduktioner. Programmering identifierades som en effektiv transduktiv länk mellan matematisk formulering och animation. En transduktiv länk hjälper till att genomföra transduktionen genom att göra den mer förståelig och följsam för studenten. En lärare som använder tal och gester för att underlätta rörelsen från formel till graf använder dem som transduktiva länkar.

Aktiva och passiva transduktioner beskriver hur en student utför en transduktion och hur en observatör kan extrahera någon information kring studentens disciplinära urskiljande, eller förståelse, av konceptet i fråga. Om transduktionen är aktiv så kan någon information erhållas som kan kopplas till förståelse av det underliggande konceptet. Men om transduktionen är passiv kan ingen information extraheras. Aktiva och passiva transduktioner är definierade i termer av *visat engagemang* som bygger på idén att studenten måste visa att hen har engagerat sig med material genom att antingen packa upp det; filtrera olika aspekter; eller markera olika aspekter.

Nästa steg i förståelsen av studenters användande av representation var att jämföra det socialsemiotiska ramverket med teorin om register för semiotiska representationer (ett annat ramverk som också bygger på semiotik). Båda ramverkan har identifierat samma typ av semiotiska fenomen som relevanta i lärandet av fysik, så som rörelsen mellan olika typer av representationer. Studier kan använda båda ramverken för att skapa en mer detaljerad och djupare beskrivning av lärandesituationen i fysikundervisning.

Ett annat sätt att förstå semiotiska resurser kommer i form av en matematisk konstruktion av konceptet. En matematisk model av semiotiska resurser skapades för att lättare kunna förstå och jämföra olika semiotiska resurser med varandra, så som en text och en bild, från ett meningsskapande perspektiv. Modellen bygger på ett dual-space-ramverk från matematiken för att modellera semiotiska resurser som en summa av urskiljbara aspekter. Genom idén om urskiljbara aspekter kan två semiotiska resurser nu jämföras med varandra, även om de ser ut att vara extremt olika, så som gester och en film. Genom att introducera operatorer till modellen kan förändringar av semiotiska resurser modelleras och ordningen av operatorer är identifierade som en relevant del i lärande processen. Denna observation baseras på *flipped classroom*, en lärandeaktivitet där studenterna först läser genom materialet innan de går till lektionen. Ett upplägg som har visat sig producera bättre resultat jämfört med en omvänd situation.

I den matematiska modellen kan lärandesituationen modelleras som ett stort antal urskiljbara aspekter som är grupperade i olika semiotiska resurser. Studentens fokus rör sig mellan olika urskiljbara aspekter som studenten finner relevanta. Studentens relevansstruktur kan urskiljas från vilka urskiljbara aspekter hen väljer att fokusera på. Som beskrivet ovan, studentens relevansstruktur kan sedan användas för att implementera olika interventioner som hjälper henom urskilja nya aspekter eller visar hur aspekterna är relevant för situationen.

I grunden så beskriver denna avhandling hur studenterna använder semiotiska resurser för att förstå koncept i fysik. Denna beskrivning har gjorts med en socialsemiotisk lins som sedan har övergått i en matematisk model av semiotiska resurser.

Preface

What is Physics Education Research?

Physics Education Research (PER) is a field of research that aims to investigate and describe the learning and understanding of physics knowledge. PER is a field of *Discipline Based Education Research* (DBER) that takes into account the disciplinary content that needs to be understood by a student in physics. For example, the PER field studies specific concepts or ideas from the physics discipline and how students learn these concepts, and what problems the students face when they investigate these specific problems. To do this, a researcher in the PER field must have knowledge of both physics and education research.

There are several ways to study how students learn physics, depending on the type of question you wish to answer. For example, a class of students may be observed over several years to study how their skills develop and how they transition from being novices to experts within the physics discipline; or a single laboratory exercise may be examined to understand what it affords the students; or the learning process may be explored using different theoretical frameworks in a physics discipline setting; or the cultural and social aspects that influence physics education can be explored. The research in this thesis study how meaning-making is made possible, with respect to physics content, using specific tools in simulated learning environments.

My path into Physics Education Research

That I would join the PER field was not a career path I had ever imagined. I was unaware that the field of PER existed before I started this PhD-journey. I probably assumed it existed, in the same way that you assume that there is always someone researching anything and everything under, over, and including, the sun. Yet the inklings were there, the first one can be found during my third year of upper secondary school when I added an additional part to my tasks in a group project about performing physics experiments, together with Jönköping University, and presenting the results. My extra goal was to present the ideas of

Special Relativity, *Quantum Mechanics* (QM), and *Big Bang* (BB) as a series of lectures for the rest of the school.

The second inkling was during my time as a engineering physics student at Lund University when I worked part time at the Vattenhallen Science Centre. Here I guided school classes and performed different demonstrations, designed to showcase some phenomenon related to physics, mathematics, biology, or chemistry. I really enjoyed the work and designed a science show (Svensson and Zamudio, 2015) and a programming workshop when I was there. The programming workshop will return in papers I and II. As I learned more physics in my studies, I did more and more outreach activities that involved teaching physics.

Both these inklings shows that I had a strong interest for making physics more understandable and interesting to my peers and looking back at my interest; it is clear that I would have a foot in the PER field one way or another. When this PhD-position was announced, it opened my eyes for the field of physics education research. A field I did not know existed, but that would capture my interest entirely.

Physics Education Research is a young research field

Physics education research as a field is young compared to research in many other fields of physics. It also differ in nature in many aspects but not in its fundamental approach to research. Since it is young, it can be said to be fragmented in its body of knowledge. In PER, it is not possible to predict the exact outcome of a learning situation, instead we can describe how different interventions, activities, enhance the possibility for learning to take place. However, there exists no way to predict the statistical outcome from any learning activity. Its effect can only be measured afterwards. PER has not had its Newton, Maxwell, or Einstein, that has put everything into neat equations or formulas. PER has a large number of theoretical frameworks that it can use to explain or investigate different learning situations but no single unifying theory that can be applied for all situations. Each framework provides answers to some questions, but it is very hard to move between two frameworks or to compare the answers between them.

Compared to the physics discipline, where there are some unifying underlying theory that you may fall back on when some strange signal enters your detector, PERs underlying theory is not there yet.[1]

[1] I should be clear; not all physics is like that, but there are some nice theorems and ideas that may be used as a basis for the analysis or to be expanded upon in physics research.

My research

In this thesis, you will follow my journey as a PhD student and gain insight into the PER discipline and my research within this discipline. As alluded to above, I started my research in studying how programming may be used as a tool to understand physics concepts. This research is summarised in papers I and II.

The papers say: programming can, and should, be used as tool for meaning-making in physics education if: the students are proficient in programming; the students are allowed to iterate on, and explore, their own models; the students construct and implement their own models. Programming should not be used in physics education if the students only follow a set of instructions to produce a specific result.

The next step of the research was a forage in the theoretical frameworks used to explain the findings from the programming project. One important aspect of the learning situation, according to the theoretical frameworks used in the research, is the movement between different types of representations. For example, a formula is a type of representation and a graph is another type of representation, and physics students must be able to move between them. Papers III and IV expands upon the idea of moving between different types of representations, which is known as transduction.

Paper III introduces the ideas of *Transductive Links* and *Transductive chains*, and paper IV describes types of transductions; active and passive transductions. Transductive links describe the role of gestures, body language, and other meaning-making actions that are taken when moving between two different types of representations, such as from a formula to a graph. A transductive chain is just many links used together, or after each other. Both concepts may be used to plan and optimise learning activities to make possible discernment for the student and to encourage meaning-making with respect to *Disciplinary Relevant Aspects* (DRA).

After paper III, an international project with Dr. Esmeralda Campos was initiated to compare the the theoretical frameworks of *Social Semiotics* (SS) as developed and explored by Airey and Linder (2017); Halliday (1978); Bezemer and Kress (2008); van Leeuwen (2004), and *The Theory of Registers of Semiotic Representations* (TRSR) as described and used by Duval (2006); Duval and Sáenz-Ludlow (2016); Campos et al. (2020). Both frameworks tries to describe the meaning-making process by describing the students', and the discipline's, use of representations to communicate and make meaning. Papers IV and V are the current academic output for this project. The data used in IV and V were collected for a separate project; a study to examine the guiding principles for constructing representations for use in physics education based on the theoretical frameworks of SS and *Variation Theory of Learning* (VTL). The analysis for the study is not complete, but will be presented in paper VI.

Paper IV defines active and passive transductions and connects them to assessing the students disciplinary discernment. Active and passive transductions aims to describe the student's shown engagement with the concept, or physics idea, under investigation during a transduction.

Paper V identifies the overlap and the differences between theoretical constructs SS and TRSR. Both frameworks identify the movement between different representations to be important for the learning process, as well as manipulations of the representations. The act of interacting with representations are connected to discerning (SS) and understanding (TRSR). The paper argues that results from both frameworks may be compared to each other. The paper also argues that comparing frameworks provide insights into both frameworks and opportunity for developing the different frameworks. Paper IV was a direct result of the the comparison between SS and TRSR.

After papers I and II work began on a side project that aims to describe the learning situation in a more stringent way. The new descriptive model aims to construct a mathematical framework that describes the theoretical constructs of social semiotics. The basis for the model is to describe a learning situation in terms of what discernible aspects it affords the students. Or, more precisely; what is possible to discern in a given learning situation and how does this discernibility change over the course of a learning activity? This work is initiated and presented in Paper VII.

Introduction

To learn physics, one must learn how concepts are connected to each other. For example, to understand kinematics, not only must the concept of position, velocity, and acceleration be understood but also the relationships between them. A focal area of study have been how programming may be used to explore and understand physical concepts, such as the connection between position and velocity. Programming requires the student to interpret a formula and unpack it by figuring out how to represent the physical concept in code-form. The visualisation of the resulting simulation allows the student to discern and explore phenomena directly tied to the original formula.

This thesis is about my research in the PER discipline at the Lund University Physics Education Research (LUPER)-group, which is part of the National Resource Centre for physics education (NRCF) and is located at the physics department at Lund University. The thesis aims to present my contribution to PER. To do so requires an presentation of the theoretical frameworks used in the papers, the methodologies, results and implications of the research. The field of PER studies how students learn and communicate physics, and this includes many different factors such as: the learning environment, the tools, the group dynamic, socio-economic effects, equality, curriculum, outreach, and technology. However, this thesis will focus on representations of physical concepts, such as, but not limited to, formulas, images, text, and the student's interaction and manipulation of these representations in a group context.

This thesis will explore what the act of interacting with formulas, and transforming them into code, offers the student with respect to the meaning-making process. It will also explore how to describe and understand the effects of different representations or visualisations as they relate to discernment and the learning process.

This is done by first introducing the aims and research questions of the different projects that make up the research in this thesis. In total, two separate projects were performed during the PhD. The first project focused on understanding how programming could be used to aid the learning of physics, from a practical perspective, but also from a theoretical perspective. The second project focused on examining how SS and VTL can guide the construction of representations for use in PER. However, several of the papers are connected to both projects and can not be seen as only connected to one of them. After the aims and research questions comes an overview of PER in the form a short literature overview. The literature overview is intended to introduce the PER field and to situate my research within it. Then comes the theoretical framework chapter that introduces SS and VTL, and how they are used in the research. The frameworks provide a lens, and a language, for how to analyse, discuss, and present collected data and results. Following the frameworks is the methodologies that have been employed to determine research questions, gather data, and analyse the data, together with a section on the ethics and data management. When the analysis is complete, comes the time for the results. The results are coupled with a section on trustworthiness that aims to showcase how and why these results can be trusted. After the results comes the discussion, conclusions, and implications, that aim to describe and showcase how the results can be interpreted and used in physics education and PER. The thesis ends with a short summary and a list of my contributions to the PER-field.

Aims

The overarching aims of the research presented in this thesis are separated into two parts. The first part relates to understanding programming as a tool for meaning-making. The second part pertains to describing the learning situation in greater detail using SS.

Understanding programming as a tool for meaning-making

Papers I and II aims to describe how programming can be used as a tool for meaning-making in physics education. The term programming encompasses the process of creating a model that may be implemented, the code itself, the structure of the code, and the visualisation of the code. Each of the step is a necessary aspect of creating a meaning-making resource to be used to examine and explore some type of physical phenomenon.

Describing the learning situation

Papers III, IV, V, VI, and VII can all be situated within the aim of better describing the learning situation within physics education. By using, and expanding upon, SS and VTL, the goal is to describe the learning situation in such a way that provide a deeper understanding of the learning situation itself and to how the students are engaging with the representations presented to them as part of the learning situation.

Research questions

Based on the aims, a number of research questions were constructed to guide this research. In the boxes below is the title of each paper and the research questions for each paper. Some of the titles, or questions, may change as not all papers are published yet, especially paper VI.

Paper I

Paper I focuses on a pilot study wherein upper secondary school students participated in a workshop where they programmed smaller physics simulations and a particle-based physics engine.

Paper I: Programming as a semiotic system to support physics students' construction of meaning: A pilot study

How can Social Semiotics be used to describe learning physics using programming as a semiotic system, based on the reported experiences by the students?

What does the participating students report about using programming to explore and learn physics?

Svensson, K., Eriksson, U., Pendrill, A.-M., and Ouattara, L. (2020). Programming as a semiotic system to support physics students' construction of meaning: A pilot study. *Journal of Physics: Conference Series*, 1512(1):1–12.

Paper II

Paper II focuses on programming itself and what it affords the students and if the students take advantage of these affordances.

Paper II: Programming and its Affordances for Physics Education – A Social Semiotic and Variation Theory Approach to Learning Physics

How does programming help students to make predictions about their model or system?

In what ways do the students create variation in the visualisation to increase the discernibility of different aspects?

How much programming knowledge do the students think is needed to use programming to explore and implement different physical concepts?

Svensson, K., Eriksson, U., and Pendrill, A.-M. (2020). Programming and its affordances for physics education: A social semiotic and variation theory approach to learning physics. *Physical Review Physics Education Research*, 16(1):1–15.

Paper III

Paper III defines the theoretical constructs *Transductive Links* and *Transductive Chains*. These concepts help to better describe the role of different *Semiotic Systems* and provides a language for talking about the flow of *Semiotic Material*.

Paper III: Concept of a Transductive Link

How can a new theoretical construct, based upon the transduction concept, help to better understand the flow and dynamics of the learning situation?

Svensson, K. and Eriksson, U. (2020). Concept of a transductive link. *Physical Review Physics Education Research*, 16(2):26101.

Paper IV

Paper IV defines the constructs of *Active* and *Passive* transductions by building on already established work. The new constructs are connected to the *Anatomy of Disciplinary Discernment* (ADD) (Eriksson et al., 2014) and implications for assessment as well as the construction of assessments are explored.

Paper IV: Active and Passive Transductions - Definitions and implications for learning

How may a new classification of transductions help with the assessment and evaluation of students disciplinary discernment?

Svensson, K., Lundqvist, J., Campos, E., and Eriksson, U. (2021). Active and passive transductions – definitions and implications for learning. *European Journal Physics,* 43 025705.

Paper V

Paper V compares the two theoretical frameworks of SS and TRSR. The two frameworks are based on semiotics (see e.g., Joseph, 2012; Peirce, 1998) and the paper found that they may be used in tandem if special care is taken to when each framework is applied.

Paper V: How do students use representations in physics? A comparison of two semiotic perspectives

How can the theoretical frameworks of SS and TRSR be used together in physics education research?

How do the theoretical constructs within the two theoretical frameworks of SS and TRSR align with each other?

Does a comparison between two theoretical framework provide some added value to the understanding and development of the two frameworks?

Svensson, K., Campos. E., (2022). How do students use representations in physics? A comparison of two semiotic perspectives *Physical Review Physics Education Research* – submitted

Paper VI

Paper VI examines SS, VTL, and empirical data, to construct a set of guidelines to be followed whenever a new representation is to be constructed for use in physics education. The analysis for this paper is not complete, and the scope and research question may change.

Paper VI: Constructing representations based on Social Semiotics and Variation Theory

What guiding principles, for constructing representations for use in the meaning-making process in physics education, can be extracted from students use of representations and from the theoretical frameworks of SS and VTL?

Svensson, K., (202X). Constructing representations based on Social Semiotics and Variation Theory – draft

Paper VII

Paper VII introduces a toy-model for comparing and analysing the dynamics of *Semiotic Resources*. It aims to examine semiotic resources using a mathematical framework.

Paper VII: Dynamics of semiotic resources

What insights does a mathematical representation of semiotic resources provide for the understanding of the underlying nature of using representations for meaning-making in physics education?

Svensson, K., Eriksson, U., Linder C., and Clark, J., (202X). Dynamics of semiotic resources *Physical Review Physics Education Research* – submitted

Literature Overview

Disciplinary based education research

Within the physics discipline exists some general principles that may be applied in basically all situations. Such as identifying the forces, or potentials, examining the energy or flow of energy, or dividing the system into states to study how the state of the system changes. However, in each sub-field of physics they take on different forms. The details of how the principles are applied in each situation is crucial to understanding and analysing the system in meaningful ways. Atmospheric physics will describe energy flux in a different way compared to a physicist doing simulations of structures.

The same applies to educational research and PER. Concepts and ideas that have been found in educational research can be applied in PER, or in any other Disciplinary Based Education Research (DBER) fields (National Research Council, 2012), but the implementation will, and should, depend on the specific discipline. PER aims to identify physics specific learning problems and apply lessons learned from educational research in a physics education setting. National Research Council (2012) defines the goals of DBER as (page 2):

- understand how people learn the concepts, practices, and ways of thinking of science and engineering;
- understand the nature and development of expertise in a discipline;
- help identify and measure appropriate learning objectives and instructional approaches that advance students toward those objectives;
- contribute to the knowledge base in a way that can guide the translation of DBER findings to classroom practice; and
- identify approaches to make science and engineering education broad and inclusive.

PER is a part of DBER, in the same manner as atomic physics is part of physics. DBER focuses on disciplinary content when describing and analysing data (National Research Council, 2012; Henderson et al., 2017). In PER, the focus lies in investigating what students think, or understand, about specific physical concepts, such as circular motion (Eriksson et al., 2020), representations of thermal phenomena (Samuelsson et al., 2019) or learning of physics using digital tools (see e.g., papers I and II, Euler et al. (2020, 2019)). Thus, research in PER examines specific learning activities in a physics context. This means that the physics content is always an important part of the research. Hence the focus of PER is on how different physics concepts are understood, learned, discussed, or engaged with. Each concept will have its own problems, and a specific learning activity for one concept may not work for another. For example, it is hard to devise a laboratory exercise that allows the student to experience the inside of the sun, but it easy to construct a laboratory exercise that allows them to experience friction. Some ideas and concepts are easier to access for students, such as mechanics and kinematics and students' understanding of mechanics and/or kinematics have been investigated by, for example, Gunstone (1987); McDermott (1984); Sutopo and Waldrip (2013); Lee et al. (2006); Ates and Cataloglu (2007); Eriksson et al. (2020). It is one of the most researched areas in PER and is often performed with first year students because it is often one of the first courses in university physics education. However, other areas have also been examined, for example electricity and circuits, magnetism, and electromagnetism. Each area of physics often come with its own hard-to-understand concepts, such as the right-hand rule, Kirchhoff's Laws, or Maxwell's equations, each introducing its own potential meaning-making problems for the students. The area of electromagnetism and its related fields of circuits, magnetism, and electricity, have been researched by, for example, Campos et al. (2020); Fredlund et al. (2014); Engelhardt and Beichner (2003); Maloney et al. (2001); Chang and Shieh (2018); Fatmaryanti et al. (2017); Ding et al. (2006).

Quantum physics brings with it many new conceptual ideas that a student must grapple with. These ideas include concepts like complex wave functions, delayed-measurements, collapse of wave functions, tunnelling. Rodríguez and Niaz (2004); Netzell (2014); Stadermann and Goedhart (2020); Maftei and Maftei (2011); Singh (2001); Greca and Freire (2003) all studied student understanding of atoms or quantum phenomena.

Other areas of physics have been studied, such as Waves, diffraction, optics, superposition and other phenomena related to waves by Fredlund et al. (2014, 2015a); Ambrose et al. (1999); Kryjevskaia et al. (2012); Mešić et al. (2019); Dido et al. (2021).

Each area brings with it its own problems, its own specific flavour that needs to be considered and addressed when designing a learning activity. DBER attempts to capture this nature by acknowledging that PER is different from *Chemistry Education Research* or *Geoscience Education Research* because they are treating ideas in different contexts. Each discipline needs to examine their own concepts and ideas and build a library of knowledge around them with respect to learning and teaching. Different DBER disciplines will have overlap in their findings and in their models. For example, chemistry and physics both use representations, such as diagrams, formulas, images, to convey meaning about abstract concepts. Thus, a study into the general idea of representations may be beneficial to both PER and chemistry education research. However, both fields may apply the findings in different ways, depending on the disciplinary context.

The physics education research triangle

To understand the field of PER, it may be divided into three different areas; *Exploration*, *Explanation*, and *Application*. Studies performed within the PER-field may be situated within the PER-triangle, as seen in Figure 1. The three different areas of PER were all developed in parallel through the history of PER. The exploration area contains research aimed at finding out new aspects of PER. The explanation area captures studies aimed at explaining the observed phenomena found in the exploration area. The application area captures studies that aim to implement or test new learning activities, assessments, or curricula.

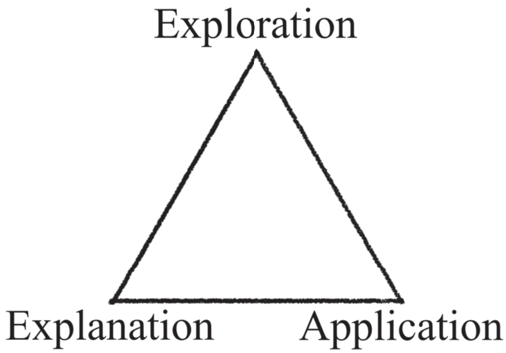


Figure 1: The PER-triangle divides the PER-field into exploration, explanation, and application. Studies may be placed within the triangle based on what the study focuses on.

Many researchers would agree that Lillian McDermott is one of the founders of the PER field (Cummings, 2011) and this overview will start there as well. Lillian McDermott established the first PER-group at the University of Washington and began offering PhD programs in the late 1970's. Work on physics education had been done before, see for example, Spears and Zollman (1977) work on structured versus unstructured laboratory activities and its effects on student's understanding of the process of science. Other influential early physics education researchers were Reif et al. (1976) who built on previous work on problem solving but applied it in a physics context. Arons (1983, 1981) studied the broader idea of literacy in science and presented a number of suggestions for how to achieve a higher literacy in science, and specifically in physics. Others, such as Trowbridge and McDermott (1981) and Goldberg and McDermott (1986) investigated different physical phenomena and how students' reason around these phenomena.

Shortly before McDermott established the first PER-group at the University of Washington, Wally Feurzeig, Seymour Papert, and Cynthia Solomon developed the *Logo* programming language (Abelson et al., 1974). The Logo language is credited by Andrea diSessa (Disessa, 1987, p. 358) as "... being the most significant innovation in information technology and education in the last decade." Logo is a language that is used to draw dots or lines in a window by specifying a number of commands and in the book *Turtle Geometry* Abelson and DiSessa (1981) uses Logo to explore mathematical ideas. This approach to using programming to explore another discipline is mirrored in papers I and II of this thesis. Seymour Papert further developed the Mindstorms language, which is based on Logo, to control robots through the same type of commands used to control turtles in the Turtle Geometry book.

At the same time as programming was being developed and identified as a useful tool for learning (in mathematics education at the time), McDermott, and other early PER scholars (e.g, diSessa, 1993), found was that students were relatively good at solving physics problems, but had a hard time describing the physics behind the problems. The students lacked a conceptual understanding of the physics.

Exploration

After the discovery that students were unable to display conceptual understanding of physical concepts despite being able to solve complicated calculation problems, a need arose to measure the conceptual understanding of students (Heron and McDermott, 1998). This was done by e.g., Hestenes et al. (1992) who developed the *Force Concept Inventory* (FCI) to test students conceptual understanding of the concept of Newtonian *Forces*. The FCI is a list of multiple choice physics questions and based on the answers, researchers may extract knowledge about student's conceptual understanding of forces. The FCI has been thoroughly validated and updated over the years and is now a tool that universities all over the world use to evaluate their students' conceptual pre– and post–understanding (see e.g., Caballero et al., 2012; Hake, 1998).

FCI and quantitative gains

With the introduction of the FCI, it became possible to set a value on students' conceptual understanding and follow how this understanding develops throughout their educational journey. A standardised measure was developed, *gain*, which is defined as:

$$g = \frac{\%_{\text{post}} - \%_{\text{pre}}}{100\% - \%_{\text{pre}}}. \tag{1}$$

Where $\%_{\text{pre}}$ are the FCI results before a course/intervention/learning activity and $\%_{\text{post}}$ is the FCI results after the student has experienced the course/intervention/learning activity. The result of for formula, g, represents how much the students' conceptual understanding has changed as a result of the learning activity they took part in. As such, the FCI has been a useful tool to evaluate different types of new learning activities (Coletta and Phillips, 2005; Caballero et al., 2012; Korff et al., 2016). If there is no gain after a student has gone through a course, the course did not alter the students conceptual understanding of, in the case of FCI, forces.

The success of the FCI showcased that it is possible to measure students' conceptual gain with respect to the concept of Newtonian forces. This prompted the development of other concept inventories for other subjects within physics and for other disciplines. Some of the most used ones are the *Force and Motion Conceptual Evaluation* (FMCE), developed by Thornton and Sokoloff (1998) to assess students' understanding of Newtonian mechanics; the *Conceptual Survey of Electricity and Magnetism* (CSEM), developed by Maloney et al. (2001) to assess students' knowledge about topics in introductory electricity and magnetism; and the *Determining and Interpreting Resistive Electric Circuits Concepts Test* (DIRECT), developed by Engelhardt and Beichner (2003). Beyond these most prevalent concept inventories, there are many others that have been developed in the areas of : basic concepts in calculus-based introductory electro-magnetism courses (Ding et al., 2006), quantum mechanics concepts such as measurement, time evolution and wave functions (Goldhaber et al., 2009; Sadaghiani and Pollock, 2015; Falk, 2007), concepts from special relativity, such as causality, first, second, and third postulate, and length contraction (Aslanides and Savage, 2013), energy related concepts, such as thermal energy, potential and kinetic energy, energy conversions (Swackhamer et al., 2005; Singh and Rosengrant, 2003), light phenomena and the interrelationships of wavelength, frequency, energy, and speed (Bardar et al., 2009; Thapa and Lakshminarayanan, 2014).[2]

The problems with concept inventories

The concept inventories described above have been applied successfully as a tool to measure the effects of different learning activities with respect to students' conceptual understanding. However, the different concept inventories do not provide us with any information of *how*

[2]For a more comprehensive list of different concept inventories, see `https://cgi.tu-harburg.de/~zllwww/fachdidaktik/ci/?lang=en` and a list compiled by Buxner et al. (2011).

this understanding was gained. It is similar to, for instance, first measuring the energy of a system to be 5 Joules and after some unknown event the measurement shows 2 Joules. The system lost energy, but no information about how the system lost energy was gained. In Figure 2 a schematic picture that captures this problem is shown. The black box in the middle of Figure 2 represents the unknown system that affects students in some manner.

Figure 2: The concept inventories are essentially testing the students before and after a learning situation. The black box represents the learning situation. The concept inventories provide no insight into what goes on inside the black box, only that it has had an effect.

To gain any knowledge of how the unknown black box affects the student, the learning situation needs to be modelled, or have some information about changes in the learning activity. Using concept inventories as a measure of conceptual gain should be done if the implemented change, or learning activity, is examined and understood. This provides a context for the numbers and may make them understandable.

Biases in the FCI

The FCI has been investigated for biases and different concerns based on how it is applied and if the results from it can be trusted. The concerns relate to if students take the FCI seriously if it is not graded, or if the results can be trusted when it is the same test for both the pre– and post–test. However, Henderson (2002) explored these questions and found that such concerns were unfounded.

The context of the questions have been shown to affect how well people can solve the problems. For example, Docktor and Heller (2008) found that there is a difference between male and female results on the FCI. McCullough and Meltzer (2001) and Mccullough (2004) also found a gender bias in the FCI and constructed a more gender-neutral version (McCullough, 2002). McCullough (2002) attribute this difference to the context the problems are presented in. Problems that were set in a stereotypical female-oriented context such as shopping, cooking, jewellery, and stuffed animals (Popp et al., 2011), were harder for males and vice versa for stereotypical male contexts. Henderson and Stewart (2018) also looked at racial and ethnicity, and found there is a similar bias as to the gender bias.

Thus, when designing concept inventories, it is not only the disciplinary content, such as physics, that is important when constructing a fair survey, but also the way in which the content is presented. The culture, gender, and background of the student can affect how they interpret the problem and this *will* affect how well they can solve the problem.

Quantitative and qualitative exploration

The concept inventories are ways to put numbers on students' conceptual understanding about different physical concepts. This is a quantitative method of gaining information about the learning situation. However, this is not the only way of describing or investigating the learning situation. Qualitative PER aims to explore the learning situation using qualitative methods, which include collecting data in the form of open answers, interviews, and artefacts, such as images, sketches and other products constructed during the learning situation. Qualitative methods provide a deeper description of the learning situation, but are much harder to generalise compared to quantitative methods (Otero et al., 2009).

Often, a qualitative pilot study is required to find problems that quantitative methods miss. For example, students' could solve problems on paper (quantitative), but when asked to explain the physics (qualitative) they failed to do so (diSessa, 1993). Mixed-methods (see e.g., Robson and McCartan, 2016) that utilise the power of both quantitative and qualitative methods are thus often recommended to obtain richer descriptions that also provide possible explanation for the observed effects.

The research presented in this thesis is qualitative, but due to the nature of programming, its tight relationship to mathematics and logic, makes it well suited to be studied using different concept inventories. By asking the students to imagine what happens in a given situation, the student may run a simple simulation in their head to produce an answer. Thus, concept inventories are a potential good match to capture the conceptual changes of programming as a tool in physics education.

Explanation

The results from different concept inventories, allows for understanding the learning situation in more detail. To try to explain the learning situation, theories or ideas must be put forward that somehow captures what is observed in a coherent model. These are commonly known as *theoretical frameworks* (discussed in the next chapter) and currently there exists a large number of different theoretical frameworks within PER, each frameworks comes with its own perspectives and assumptions that are used to describe or understanding the understanding or meaning-making process regarding physics concepts.

One of the earliest attempts is diSessa's ideas about *Phenomenological Primitives*, or *p–prims* for short (diSessa, 1993). P–prims are fundamental ideas about physical phenomena that are build up from student's lived experiences of interacting with the world. An example of a p-prim could be; "the heavier an object is, the larger object must be". That is, an observation that has be observed in a specific scenario is extrapolated to be valid in all scenarios. However, many p–prims provide erroneous conclusions when applied outside the context of their original conception. In the provided example, if more mass is added to an object, it will become larger. However, if two different objects with different masses are compared to each other, the more massive object does not need to be larger than the lighter object. The 'phenomenological' aspect of p–prims refers to the observation of them as personal experiences (diSessa, 2015). diSessa has constructed a long list of observed p–prims present within the physics student populace. By knowing and understanding these p–prims, interventions can be designed to address them so that students go from these naive understandings to a deeper understanding. P–prims are part of the *Knowledge in Pieces* (KiP) approach to understanding learning and knowledge (diSessa, 1988), that aims to describe difficult-to-learn concepts within the *Conceptual Change* framework. Vosniadou (2013) describes different types of conceptual change and introduces the framework theory approach to explaining the different types of conceptual change. Conceptual change, p-prims and the KiP ideas are based on cognitive ideas and attempts to describe what happens inside the students head. Other cognitive approaches that are used in PER are *Cognitive Load Theory* (CLT) (see e.g., Paas and Merriënboer, 2020; Chandler and Sweller, 1991), and the *Resources Framework* (RF) as introduced by Redish (2004). Both CLT and RF describes what "resources" students have access to, either with respect to recalling or making associations between aspects, or with respect to cognitive tools they can employ to analyse the situation in front of them.

Many more theoretical frameworks have been developed within and alongside PER, and I will explore some in detail in the research presented in this thesis. Some frameworks aim to describe the learning situation in a meaningful way such that new information can be gained or so that new inferences can be made. Other frameworks aim to describe the cognitive aspects of learning, some describe learning with a psychological lens, or socio-economic, cultural, learning environment, representational, communicative, or with a combination of each.

Representational approach

The main frameworks used in this thesis are SS and VTL, and both are heavily tied to representations. Representations are based on the idea of *Semiotics*, as initiated by Ferdinand de Saussure (see e.g., Joseph, 2012), or Charles Sanders Peirce (see e.g., Peirce, 1998). Both de Saussure and Peirce identifies the notion of signs as a fundamental idea when communicating ideas. The meaning and the meaning-making process involves the creation, interpretation and manipulation of these signs. In PER, the signs are often identified with representations. Representations are (in physics), for example, formulas, graphs, images, animations, text, or other ”objects” that aim to represent a specific concept or idea. In SS, representations clumped together with activities and tools to create semiotic resources (Airey and Linder, 2017).

Tytler and Prain (2009) argues that representation based approaches are distinct from cognitive approaches for investigating learning in science. They especially argue that the cognitive ideas may be re-interpreted as development of student's representational resources. Prain and Tytler (2012); Tytler et al. (2013) states that by studying how students construct and manipulate representations, knowledge can be gained with respect the students learning of concepts.

SS and VTL uses representations to analyse and explain the meaning-making process. Another framework is the TRSR, by Duval (2006), that studies student understanding of mathematical concepts by describing and analysing the students usage of representations, such as how students move between graphs, formulas, and sketches that represent a single mathematical object, for example a vector field.

The frameworks of SS and VTL are explored in another chapter and will not be explored here, however the research in this thesis is very much situated in the development and understanding of SS, which is a theoretical framework (Airey and Linder, 2017; Halliday, 1978, 2009; van Leeuwen, 2004) constructed to analyse and understand the construction and use of specialised systems of communication within different social groups. In this work, SS is applied within the PER discipline, to study how meaning is constructed in a social setting using specialised representations.

Application

This section will present some of the ways the results and theories have been applied to teaching and learning to improve the physics education at university level education.

One of the earliest researched-based methods to teaching physics was the *Physics by Inquiry* (PbI) developed by McDermott et al. (2000). McDermott and Shaffer (1992) argued for a research-based curriculum development of physics education and developed an inquiry based on the instructional approach of guided inquiries. PbI uses a carefully crafted sequence of learning activities where an instructor prompts the advancement in the sequence through the use of guided inquires. There is a focus on developing conceptual models and exploring ideas. This method allows students to confront their own naive conceptions of physics concepts. The PbI can be seen as an adaption of the socratic method which is a method where questions are used to stimulate critical thinking and to investigate different concepts and ideas (see for example, Phillip E. Areeda (1990)).

Another learning activity is Washington *Tutorials* (McDermott et al., 2002) which is a set of worksheets that aims to develop the conceptual understanding of different physics concepts. These worksheets were developed by the Physics Education Group at the University of Washington. *Tutorials* are group-based learning activities where small groups of students discuss different physical concepts.

Learning activities

Tutorials and Physics by Inquiry are examples of constructing new learning activities with the aim of increasing the students' conceptual understanding. Several other new learning activities were developed, such as *Modeling Instruction* (MI) by Brewe et al. (2009). MI, as the name suggests, is based on the modelling process (e.g., Hestenes, 1987) and making students go through every step of it; development, evaluation and application of the model. MI-based learning activities have produced increased conceptual understanding, as measured by different concept inventories (e.g., Jackson et al., 2008; Durden and Hinrichs, 2019).

Learning activities from the broader education research field has also been incorporated into PER. Such as Vygotsky (1997), with his ideas of *Zone of Proximal Development* (ZPD) and scaffolding. The ZPD describes three zones in the learners potential learning progression. The first zone is where the learner can perform the task on their own with no outside influence. Vygotsky calls this the *Actual Development Level*. The second level is the zone where a learner needs a guide, or support, to be able to explore. The third level is where the learner has no chance to explore or understand, even with a guide or a support structure. Vygotsky used these levels to determine the mental level of children. However, that is not how the ideas are employed in PER. In PER, the idea of a support or guided zone is used to introduce the notion of scaffolding to structure the learning activity in such a way that difficult problems or concepts can be explored and understood by the students (see e.g., Ahmed Malik, 2017). Scaffolding is about providing just enough help for the students to start exploring on their own such that they may begin to construct their own meaning. If too much help is provided, students may turn into passive learners which hinders their growth (Verenikina, 2003; Shabani et al., 2010).

Active Learning (see e.g., Kyriacou, 1992) is another framework used to guide the application or construction of new learning activities. AL is learner-centered and focusing on the active participation of each student. Through discussion, reflection, and engagement, students are immersed in a learning environment that affords meaning-making about the specific concept under consideration.

Each new method of teaching and learning has some underlying aspects in common; They all aim to introduce the disciplinary content to the student in a new way. The new way is designed so that the student can experience different aspects of the disciplinary content through different semiotic systems. MI provides access to disciplinary content through different lenses: development, evaluation and application. Each lens forces the student to engage with the disciplinary content with a different outlook, making possible a multifaceted way of understanding the disciplinary content. However, each learning activity has a different approach to implementing this change, which means that they may not be compatible with each other. An instructor is thus required to understand the learning activity they wish to implement, so that it is applicable in their situation. For example, AL requires student discussions and engagement, which often requires a learning environment (active learning environment) where the students can discuss freely with their peers.

Programming as a learning activity

Programming was also introduced to physics students as a new way to explore different phenomena (Redish and Wilson, 1993). As Logo, through *Turtle Geometry* (Abelson and DiSessa, 1981), had been used to explore mathematics, as was M.U.P.P.E.T (Maryland University Project in Physics Education Technology) (Redish and Wilson, 1993) introduced to the students to explore ideas in physics, but also to explore what programming could mean for the structure of physics education. Although M.U.P.P.E.T included ways to plot a graph the outputs of the program, it would be considered clunky and difficult to work with compared to today's standard.

It can be argued that programming, as a tool to investigate physics, did not, and have not, expanded to become a main source of meaning-making in physics education, because of the difficulty of making interesting and useful visualisations. However, in 2000, David Scherer, together with Ruth Chabay and Bruce Sherwoord, creates VPython (Scherer et al., 2000). VPython is an extension to Python, a programming language (van Rossum, 1995), that introduces easy to use 3D graphics. Using VPython as a basis for exploring physical phenomena, Chabay and Sherwoord created the *Matter and Interactions* (Chabay and Sherwood, 2015) textbook to teach physics using programming.

Programming is used in physics research to make simulations and to manipulate and analyse data. This is also how programming is often introduced to the students, for example, at the University of Oslo (UiO), the Center for Computing in Science Education (CCSE) has incorporated programming in their physics curriculum with the aim to increase the computational competence of the students and to prepare them for physics research. However, papers I and II, argue for a different implementation of programming that is not focused on learning physics-related skills, but is focused on exploring the physics itself through the implementation of code, the creation of models and the interaction with visualisations. With the ease of visualising aspects of simulations (using VPython or other tools) programming has the potential to become a useful tool to explore and investigate physics model, both quantitative and qualitative.

Situating my research within PER

The research that will be presented in this thesis is situated within the PER field and it is divided into two projects. Below, a short literature review is provided that is aimed to contextualise each project with respect to the larger PER field. In Figure 3, papers I through VII are placed within the PER-triangle to showcase where the research presented in this thesis, fits within the PER-field.

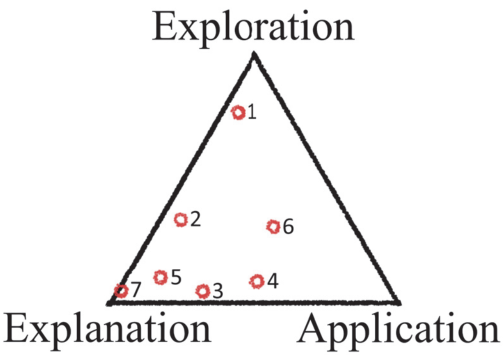


Figure 3: The PER-triangle with papers 1–7 (published and drafts).

Programming in PER

The first project, relating to papers I, II, and III, aimed to investigate the idea of using programming as a tool for meaning-making in physics education. The idea of using programming in physics education is not new, but it appears to be an area that has emerged separately during the ages[3].

Programming has already been used in physics education and has been studied by the physics education research community, as described in the literature overview chapter. Much of the early research into using programming in physics education identifies the potential programming as a tool to explore and investigate physics phenomena (Papert, 1983;

[3]This was the case with my research as well, I was unaware of the research done on the topic when I proposed the project.

Wilson and Redish, 1986; Redish and Wilson, 1993; Bork and Ford, 1967). Redish and Wilson (1993) describes the use of programming in physics as more aligned with professionals and that professionals use computers often in their work; a student must thus learn these skills to transition into a professional physicist. Redish also describes how the use of programming can allow the student to explore complex models. For example, a double pendulum system is not possible to solve on paper, but we can solve it numerically on a computer, and if a double pendulum system can be solved, it is possible to solve a triple, a quadruple, or n-tuple pendulum, allowing the student to explore and experience the phenomenon in greater depth. diSessa (2000) describes a computational literacy that aims to capture a competence that students are required to develop if they wish to use computers and, by extension, programming to examine physical phenomena. It can be compared to *Computational Thinking*, which, as defined by (in the defining computational thinking section Denning and Tedre, 2019), is:

> ”CT is the mental skills and practices for
>
> - *designing* computations that get computers to do jobs for us, and
> - *explaining* and interpreting the world as a complex of information processes”

The definition captures both a construction aspect with the first point, as well as a interpretive aspect in the second aspect. As Prain and Tytler (2012) argues, the construction of representations provides insight into the learning process and is a central part of making meaning with regards to a concept. Explaining and interpreting the world requires reflection and discernment, both aspects are part of SS and VTL. The argument here is that papers I and II in this thesis uses SS and VTL to examine programming from a semiotics perspective while also capturing aspects that other researchers have identified as important for programming.

The definition of CT brings the idea of programming, or thinking like a programmer, outside of a coding setting. It applies the ideas of programming to everyday situations and through that lens, complex situations can be understood and analysed. This is also how the term programming should be understood in this thesis. It is not just the act of coding, it is the methodology of figuring out how to represent a concept as a program. It is the unpacking of aspects and the re-representations of them in a new form that allows for meaning-making to take place. The programming in this thesis focuses on creating simulations that the students can interact with, a concept that has proven to be advantageous to learning physics (e.g., Kulik and Kulik, 1991; Luo et al., 2018).However, using simulations in the physics classroom has produced divergent results with some finding it as good or worse than narration-based education[4] when it comes to evaluation based on test scores (e.g., Reamon and Sheppard, 1997; Rieber et al., 1990).

In the programming project, constructing models, representing them as code, creating visualisations and interactions with the visualisation were all identified to be part of the programming process. This was based on personal experience with learning through programming and making interactive visualisations, an aspect that is reflected by Schwarz (1995), who describes that the act of implementing a double pendulum system allowed for a deeper understanding of it. Computer generated visualisations have been studied before, for example by Chang et al. (2008); Naps et al. (2002); Ronen and Eliahu (2000), and visualisations, and interactive visualisations, have been found to increase the conceptual change of the students' understanding.

One of the unifying descriptions of using programming as tools for learning is that basically all proponents state that programming should be not be used in a plug'n'chug way nor in a cookie-recipe type scenario. That is; students should not just follow a step-by-step set of instructions. Naps et al. (2002) emphasises that there should be some type of active learning for the student, which means that they should be engaging with the program or simulation in at least one of the following ways:

- Constructing their own input data sets
- Making predictions regarding future visualisation states
- Programming the target algorithm
- Answering strategic questions about the visualisation
- Constructing their own visualisations

The same ideas are expressed by Redish and Wilson (1993) and diSessa (1993), in the early days of examining programming in PER. The ideas of Naps et al. (2002) are also mirrored in papers I, II, and Luo et al. (2018).

Project 1: Programming as a tool for meaning-making in physics education

The first project was to examine *"Programming as tool for meaning–making in physics education"*. Based on previous personal experience of producing and performing a programming workshop at the Vattenhallen Science Centre, the potential of interactive simulations as a

[4]Narration-based refers to education where there is no interaction between student and lecturer: the lecturer speaks and the students take notes.

tool to investigate the underlying physical concepts had already been identified in learning situations. The project aimed to capture this experience in a documented and controlled setting. The aim of the programming was not to produce a simulation to obtain values from, but the aim was to use the process of constructing, and interacting with, the simulation to learn physics.

However, based on just the description of the project, it was not expected to find anything new from the study (see e.g., Papert, 1983, that describes how the construction of programs are beneficial to the learning process.). It was thus decided that the frameworks of SS and VTL would be used to describe and explain the findings.

Paper I is positioned in the exploratory area of the PER-triangle, as it aims to examine how the student can make use of programming as they investigate physics phenomenon. Paper II takes a more theoretical approach to explain what is observed in paper I and is placed further into the explanation area of the PER-triangle (see Figure 3). Paper III is heavily based upon ideas that emerged during this project, and is mostly a theoretical development with some hints on how to apply the ideas. Paper III is located mostly in the explanation area with a slight lean towards the application area.

Project 2: Constructing representations for physics education

After the programming project (papers I, II, III) the researched focused entirely investigating and developing the theoretical frameworks used in papers I and II. The second project: *Constructing representations for physics education*, aims to extract useful guiding principles from SS and VTL with respect to the construction of new representations for use in physics education. A secondary effect of this project was the further development of SS in papers IV and V. The project aims to incorporate the ideas of constructing representations from Prain and Tytler (2012) and Tytler et al. (2013), together with the theoretical constructs of SS and VTL, to create a holistic view of representations that captures all aspects of a representations life-cycle; its creation, manipulation, its role in communication and meaning-making.

Theoretical Frameworks

What is a theoretical framework?

To get an idea of what this chapter is about, what a theoretical framework is must first be described in more general terms before going into complex details. A theoretical framework is a set of theoretical constructs that, when used together, aims to describe the learning situation in a meaningful way. A theoretical construct is a useful concept within a framework that can be drawn upon to explain or understand phenomena observed as students learn. For example: –*Representation*– is a theoretical construct within the multimodality framework (see e.g., Bezemer and Kress, 2008; Stein, 2008) designed to describe the multitude of different ways to represent a concept. Drawings, graphs, formulas, texts, are all examples of representations and they can even be representations of the same concept. By using the idea of representations, they can be described in terms providing access to different aspects of a concept that students are to learn. For example, a drawn arrow may represent a *vector*, with a length and a direction. However, a v with a line over it, $\bar{v}$, may also be a representation of the same vector. Both representations allow for discernment or manipulation of the concept in different ways and the concept can be represented using different types of representations.

Theoretical frameworks can be compared to different ways to model physical systems in the physics discipline. Depending on what aspect you (as a researcher) are investigating, you will model the system in such a way that provide access to those aspects. If you are modelling the atmosphere, you will not model each individual atom. The atoms will be treated as a statistical aggregate and used in fluid mechanic formulas. The same is true in physics education research. Each theoretical framework is designed to study and understand a specific aspect of the learning situation. Some study the socio-economic affects on physics education (see e.g., Agbom, 2018; Semela, 2010), others look at cognitive aspects of learning (see e.g., Miller, 1956; Chandler and Sweller, 1991; Saw, 2017), and some look at the cognitive resources that students have learned and have access to, as they engage with physics content (Wittmann et al., 2019; Redish, 2003). However, these frameworks have not been studied in detail in this thesis and a nuanced description of their strengths and weaknesses will not be presented here. The frameworks used in this thesis studies student use of representations and aims to describe how representations are used in the physics discipline by experts and novices to understand and communicate disciplinary content.

My frameworks

The frameworks used in this thesis are very much focused on the meaning-making that can be done using representations. The frameworks are *Social Semiotics* (SS) and *Variation Theory of Learning* (VTL) and both have representations as a central part of their explanatory models when it comes to learning physics.

Social Semiotics

SS is the main theoretical framework used in this thesis. It aims to describe and understand the usage of representations in specialised groups. SS was first introduced in 1978 by Halliday (1978) who aimed to describe written and spoken language as a social construct designed to convey meaning within a community. As the framework was being expanded, it started to incorporate images and other media to communicate meaning. This was done by incorporating ideas from the *Multimodality* framework (Bezemer and Kress, 2008; van Leeuwen, 2004; Kress, 2009; Kress et al., 2014; Jewitt et al., 2001, 2016). Multimodality is a framework that describes how different modes are used together in communication. A mode is a way to represent a concept, such as an image, text, graph, or formula. A multimodal learning situation is a learning situation where multiple modes are used together to create meaning. This has been shown to foster better understanding and learning amongst students and is known as the multimedia effect (Mayer, 2002; Schweppe et al., 2015). SS has adopted ideas from multimodality and is now a multimodal framework that Airey and Linder (2017) (p. 95) defines as:

> "The study of the development and reproduction of specialised systems of meaning–making in particular sections of society."

SS has been applied in the PER discipline (Airey and Linder, 2009, 2017; Linder, 2013; Fredlund et al., 2014, 2015a) to describe the learning of physics. Others have applied SS to investigate specific learning situations such as programming (Svensson et al., 2020a,b), one dimensional kinematics (Eriksson et al., 2020, 2018), wave phenomena (Fredlund, 2015), astronomy (Eriksson et al., 2014; Eriksson, 2019), embodiment using interactive whiteboards and simulations (Euler et al., 2019, 2020), the use of IO-lab in physics classrooms (Volkwyn et al., 2018, 2019), and the affordances of infrared cameras (Samuelsson et al., 2019). SS has also been applied outside of physics. Patron et al. (2021) applied SS to investigate how students and teachers unpack visual representations in chemistry. Many of these investigations have also resulted in further developments of the SS framework. For example, Eriksson et al. (2014); Eriksson (2019) introduced the *Anatomy of Disciplinary Discernment* which expanded on the discernment concept and used empirical data to define a hierarchy to *disciplinary discernment*. Fredlund et al. (2015a) identified and defined *Disciplinary Relevant Aspects* for use in SS and connected them to variation theory of learning.

In short, SS is a multimodal framework that aims to describe the construction and use of meaning-making resources within specialised groups in society, and the framework has been successfully applied to describe different physics education scenarios. Much of the nomenclature of SS is directly taken from multimodality and used in the same way. Below follows a description of many of the theoretical constructs that are used within SS and a short description of how they may be used together to analyse a learning situation.

Semiotic resources

One of the basic units in SS is the construct of *Semiotic Resources* (SR) (van Leeuwen, 2004; Airey and Linder, 2017; Lemke, 1998). Semiotic resources are anything that is used to make meaning. In physics education, these could be formulas, texts, gestures, words, graphs, or images, and these are standard 'representations' as described by multimodality. But SS also includes activities and tools, such as an excursion, or a particle accelerator, in the definition of semiotic resources. Thus, anything that is used to extract, highlight, examine, understand, investigate, convey, or construct meaning is considered a semiotic resource. Fredlund et al. (2012) identified that two semiotic resources that are very similar, can have very different meaning-making potential. That is, two diagrams that show the same phenomenon may present the data in different ways. They may use dotted lines, colours, different shapes, or readable labels in their presentation. The different diagrams have different meaning-making potentials.

Semiotic systems

Semiotic resources are grouped into *Semiotic Systems* (as used by Airey and Linder, 2017; Lemke, 1998; van Leeuwen, 2004) that are built up out of similar semiotic resources. Semiotic systems are separated from each other by the types of semiotic resources they contain. Each semiotic system describe qualitatively different ways to communicate, or to represent, some semiotic material. For example, the semiotic system 'Text' is qualitatively different than 'Image' even if they are constructed to convey the same idea. A semiotic system also implicitly, or explicitly, provides instructions for how to create new semiotic resources within that semiotic system. van Leeuwen (2004) describes semiotic systems using rules that govern how semiotic resources are created and how they are to be used within specific social groups.

Semiotic material

Another central concept is the notion of *Semiotic Material*. Semiotic material is the concept (or ”content of a textual entity”, Bezemer and Kress, 2008, p. 176) that is being represented. A line with a triangle at one end (an arrow) does not have any meaning unless presented in a specific context and presented for a specific social group that can interpret it. Or, stated in another way, an arrow may have many different meanings and it is the context and social group that defines which of those meanings is the correct one. A physicist may interpret the arrow as a vector, from which the physicist may extract a direction and a magnitude. From the context, the physicist may even identify the arrow as a representation of, for example, a change in temperature. It is within a context and a social group that a specific meaning can be extracted from the semiotic resource. Semiotic resources do not have meaning without a context or outside of a social group.

The meaning a specific social group extracts from a semiotic resource, in a specific context, is the semiotic resource's semiotic material[5]. Over time, specific semiotic resources have emerged that have some agreed upon semiotic material. Such that, if a person wishes to be part of a specific social group, they must learn to discern this semiotic material from the semiotic resource. For example, the formula $\bar{\mathrm{F}} = \mathrm{m}\bar{\mathrm{a}}$ has some agreed upon meaning when engaged with in a physics context.

To become a physicist, one must be able to read graphs, formulas, gestures, text, or other semiotic resources that are of use within the physics discipline. The semiotic resources provide access to the semiotic material that is agreed upon, in the physics discipline, to be relevant.

Translations

Semiotic resources can be manipulated, or changed, as part of the student interacting with them. For example, the student may add extra lines to a graph to indicate a tangent of the plotted line. When the student adds a line to the graph, they change the semiotic resource

[5]This is an expansion of (Bezemer and Kress, 2008, p. 176) who states that semiotic material is ”content of a textual entity”. By reframing semiotic material to depend on the social group and the context, the specific semiotic material of a specific semiotic resource may be defined by that social group in a specific context.

and the meaning-making potential that it has. It is now easier to discern the tangent of the plotted line.

Multimodality (Kress, 2009; Kress et al., 2014; Bezemer and Kress, 2008; Jewitt et al., 2016) has examined this type of change to semiotic resources and have provided terms to use to describe changes to semiotic resources. The general term that describes any change to semiotic resources is *Translation*. Translation have been further subdivided into *Transformation* and *Transduction* which describes different types of changes to semiotic resources (Bezemer and Kress, 2008).

Transformation

Transformation (paraphrased from Bezemer and Kress, 2008, p.169) is the act of changing a semiotic resource, but staying with the same semiotic system. Such as rewriting a text, adding lines to a plot, or manipulating a formula. Figure 4 showcases an example of a transformation where a graph is modified to highlight some aspects, such as when the derivative is zero or the direction of the slope. Another example of a transformation is the rewriting of a research paper into a chapter in a book, or to a popular science article. The transformation is aimed at highlighting a new, or specific aspect that was missing before. The transformation may also shift the tone and intent of the semiotic resource, depending on what audience it is aimed at. This is a form of unpacking (see e.g., Airey and Eriksson, 2019).

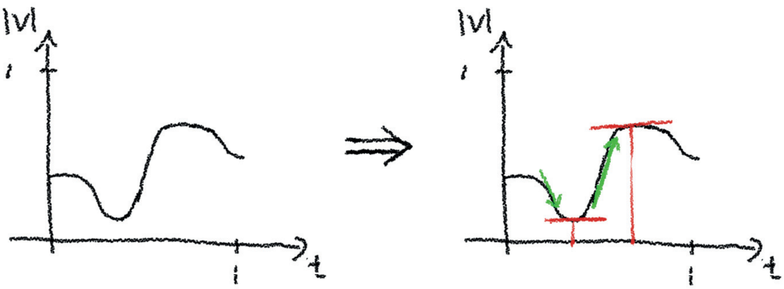


Figure 4: A graph is modified to showcase some specific features of the plot. This is called a transformation, where the change of the semiotic resource is contained within the same semiotic system.

Transduction

Transduction is the act of moving semiotic material between different semiotic systems (paraphrased from Bezemer and Kress, 2008, p. 169) such as going from a formula to a plot, or from a text to a sketch. The aim of a transduction is to re-represent the same semiotic material but in a new semiotic system. In Figure 5 a transduction is performed that takes the semiotic material in a text and represents it as a plot.

Volkwyn et al. (2019) identified three critical aspects of the transduction–process; *Transduct*, *Intensify*, and *Filtering*. However, throughout the papers and this thesis, the three critical aspects of transduction has been re-framed into: *Unpacking*, *Highlighting*, and *Filtering*. As there is an assumed transduction taking place, there is no need to state that a transduction transduct, instead the focus is directed to a process that takes place as part of the transduction: unpacking (Patron et al., 2021; Airey and Eriksson, 2019). Throughout the thesis and the papers, *intensify* has been replaced with *highlight*. This change is to further emphasise that intensification of aspects is related to making aspects stand out, or making them more discernible. Such as using a highlighter in a text to specify specific sentences or paragraphs.

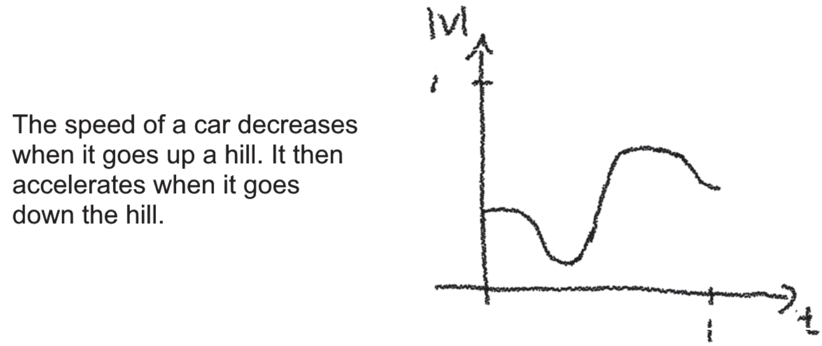


Figure 5: The semiotic material from the text is transduced into a plot. That is, they aim to represent the same idea. This is an example of a transduction; the movement of semiotic material from one semiotic system to another.

Unpacking As part of the transduction process, the transducer[6] must unpack the original semiotic resource and decide how the aspects of the semiotic resource should be represented in the new semiotic system. For example, if the divergence of a field needs to be expressed (as seen in Equation 2) in code form, each symbol needs to be unpacked with respect to what it means and addressed separately from other symbols. But, how the aspects interact with each other must also be unpacked to produce an accurate representation. Figure 6 showcases a code representation of Equation 2, and it can be seen that they are very different. A student requires disciplinary knowledge to identify that they represent the same semiotic material. Equation 2 is unpacked within the same semiotic system, a transformation, and in Figure 6, the formula has been implemented into code and further unpacked through a transduction.

[6]The person, or apparatus, performing the transduction.

$$\text{div } F = \nabla \cdot F = (\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}) \cdot (F_x, F_y, F_z) = \frac{\partial F}{\partial x} + \frac{\partial F}{\partial y} + \frac{\partial F}{\partial z} \tag{2}$$

```
def divergence(field, pos):
    return sum(gradient(field, pos));


def gradient(field, pos):
    dx = (field[floor(pos[0] - 1)] + field[floor(pos[0] + 1)]) / 2
    dy = (field[floor(pos[1] - 1)] + field[floor(pos[1] + 1)]) / 2
    dz = (field[floor(pos[2] - 1)] + field[floor(pos[2] + 1)]) / 2
    return {dx, dy, dz}
```

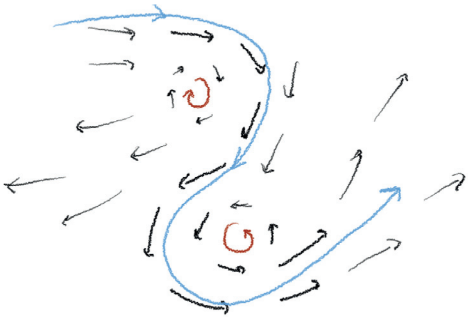
Figure 6: The divergence operator, div, is written in code form a three dimensional field. The act of writing the code requires the transducer to unpack the formula.

Patron et al. (2021) explores qualitatively different ways to unpack a representation and identified five ways to do it; by verbal explanation; by adding features, by transformation; by transduction and; by assumption. For a deeper explanation of the different ways, the reader is referred to the original paper. But Patron identified adding features, transformation, and transduction as student-centered and the other two as teacher-centered. A student-centered perspective is more pedagogical and a teacher-centered perspective is more disciplinary. That is, two disciplinary experts may assume that the other one can unpack the representation they are using when discussing an established phenomenon, they have no need to actively unpack it. However, students will have to unpack it if they are not familiar with the representation or phenomenon itself.

Highlighting One important point of the transduction is the ability to highlight (*intensify* in Volkwyn et al., 2019) specific aspects . The nature of the semiotic system of the final semiotic resource may afford the discernibility of a specific type of aspects. For example, by representing a list of data points as a vector-field plot (see Figure 7), it may be easier to discern the flow and dynamics of the field. A transduction should take advantage of semiotic systems inherent affordances to highlight specific aspects. Fredlund et al. (2021) describes the inherent affordances, of a semiotic system, as its epistemological commitment of modes that cannot be avoided when situated within that semiotic system. That is, affordances that are tied to the semiotic system and not to the representation itself. For example, the 'Image' semiotic system has 'shape' as its inherent affordance, an affordance the semiotic system 'Speech' lacks. When performing a transduction, one must use the inherent affordances to construct a new semiotic resource. Highlighting is thus related to how aspects are represented in each semiotic system.

nr	position	vector
1	[0, 0, 0]	$[x_0, y_0, z_0]$
2	[1, 0, 0]	$[x_1, y_1, z_1]$
3	[2, 0, 0]	$[x_2, y_2, z_2]$
4	[3, 0, 0]	$[x_3, y_3, z_3]$
5	[4, 0, 0]	$[x_4, y_4, z_4]$
⋮	⋮	⋮

(a)



(b)

Figure 7: When a set of data points (a) are represented in a new way (b), the new semiotic system will help highlight a specific type of aspects, related to the semiotic systems inherent affordances. Here is a sketch of a vector field with some complex dynamic, something that would be hard to discern from just a list of data points.

Filtering The third aspect that Volkwyn et al. (2019) describes is the act of filtering aspects using transduction. A part of the transduction–process is that information may be lost, or information may be added to the final representation that was not explicit in the original representation. In Figure 7, the new vector–field representation has lost all direct representation of the actual values. They have been filtered out as part of the transduction. The filtering of aspects is important when it comes to showcasing what is important. In Figure 7, it is not the values that are important, but the dynamics that can be discerned in the vector field.

Disciplinary relevant aspects

Fredlund et al. (2015b) coined the term *Disciplinary Relevant Aspects* (DRAs) and defines them as (on page 2):

> ”... those aspects of physics concepts that have particular relevance for carrying out a specific task”.

For example, to solve a mechanics problem, the forces, masses, initial state, and the like must be identified, but the connection between the different aspects must also be understood. All the different quantities and relationships are part of the DRAs, as well as any dynamic or emergent effects.

DRAs are defined for a specific situation with a specific disciplinary lens, and it is only in that context that they exists. The colour of a car is not relevant when solving a mechanics problem[7]. However, the colour of stars are very much relevant when trying to figure out

[7] Except if it is red. Red cars go faster. See Codex: Orks (4th edition) - page 93.

their mass, size, distance, chemical composition, age, and velocity. In the car example, the aspect 'colour' is not relevant to the discipline, but in the star example, it is very relevant. Fredlund et al. (2015a) describes three steps to use DRAs to inform the teaching of physics. The first step is to identify which aspects are DRAs in a given learning situation; the second step is to find or construct semiotic resources that afford these DRAs to the students; the third step is to introduce variation within the DRAs to make them visible to the students. Eriksson et al. (2020) expanded upon this list to include the student's relevance structure (Marton, 2015), as the student may discern a DRA but not find it relevant.

The aim for any learning situation is to provide access to the DRAs for the student in such a way that they can discern, manipulate, and understand the DRAs for a given situation.

Multifaceted way of knowing

An important part of learning a concept is to experience it using many different semiotic system. By experiencing it using different semiotic systems, students are provided access to different facets of a concept. It is only through a *Critical Constellation of Modes* that the student can gain a *Multifaceted Way of Knowing* (Airey and Linder, 2009, 2017). Thus, it is believed that there exists a perfect combination of semiotic resources that, when used in a pedagogical manner, provide access to all facets of a concept. However, there exists no way of discovering all facets of a concept. All facets may be exhausted, given a specific representation, such as fully describing a linear equation that is written down as an equation. But there may exist another way of representing linear equations that could provide access to another hitherto unknown facet of linear equations.

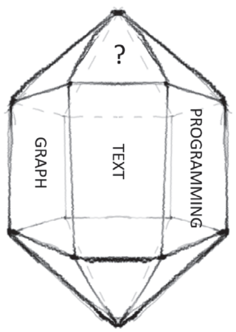


Figure 8: The many facets of the semiotic material is represented in different semiotic systems. All facets of a semiotic material are not known. Figure is a re-imagining of Figure 6 in Airey and Linder (2009).

Fluency

An important part of becoming a physicist is to become fluent in the use of different semiotic resources. A physicist must be able to read, write, and manipulate formulas, graphs, gestures, diagrams, text, animations and more, to make themselves understood within the physics discipline. On page 33, Airey and Linder (2009), defines *fluency* as:

> ”[...] a process through which handling a particular semiotic resource with respect to a given piece of disciplinary content becomes unproblematic, almost second-nature.”

However, fluency is not enough to achieve disciplinary meaning–making. Fluency is only related to the ability to read and write different semiotic resources within different semiotic systems, but it is not associated with the disciplinary meaning of those semiotic resources. Without an appreciation of the disciplinary content, or understanding what a representation actually represents, fluency may just be an indication of discourse imitation.

Discourse imitation

As discussed in the Literature Overview chapter, and explored by diSessa (1993), physics students were found to display the ability to calculate and manipulate relevant semiotic resources and semiotic systems used within the physics discipline. However, they were unable to connect the semiotic resources they had used to relevant disciplinary knowledge. Thus, they had achieved fluency, but that was not enough to obtain disciplinary understanding. Airey and Linder (2009, 2017) describes this as *Discourse Imitation*. Fluency is not enough, but an appreciation of the underlying disciplinary meaning that the semiotic resource affords is needed to obtain actual disciplinary understanding.

Disciplinary discernment

Eriksson et al. (2014); Eriksson (2019) introduces the idea of *Disciplinary Discernment* and the hierarchy used to structure it: the *Anatomy of Disciplinary Discernment* (ADD). Eriksson et al. (2014)(p. 2) defines disciplinary discernment as:

> ”Noticing something, reflecting on it, and constructing new meaning from a disciplinary perspective.”

Thus to disciplinary discern something is not just the act of noticing or observing, it is also the ability to connect it to disciplinary knowledge.

The ADD describes different levels of disciplinary discernment, see Figure 9 for a representation of this hierarchy. One of the overall learning-goals is to have the student move up the hierarchy as they interact with more semiotic resources from different semiotic system, allowing them to discern and experience a concept in new ways.

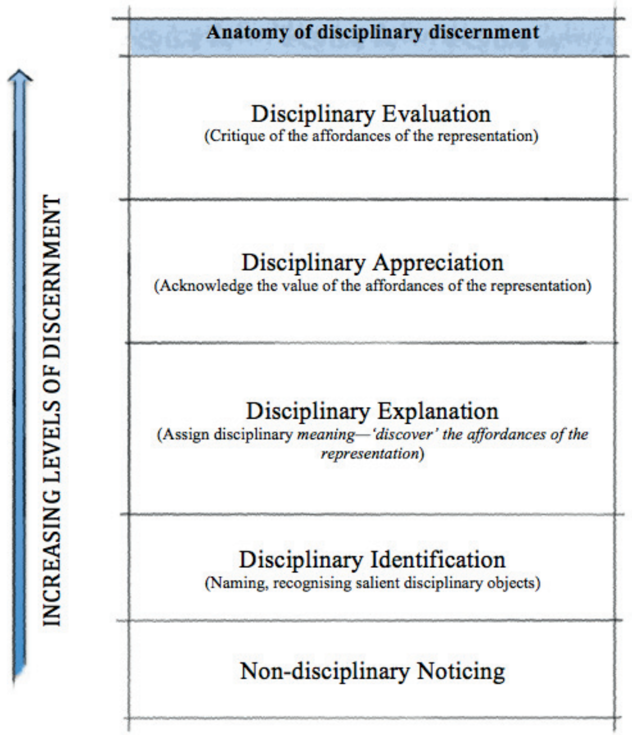


Figure 9: The Anatomy of Disciplinary Discernment. It is a hierarchy of disciplinary discernment levels. Recreated under Creative Commons Attribution 4.0 International (CC BY 4.0), original may be found in Eriksson et al. (2014).

Non-disciplinary Noticing The lowest level in the disciplinary discernment hierarchy and describes discernment of aspects but with no coupling to the disciplinary meaning. For example, a person may discern the shapes, or colour of objects in a picture, but are unable to say how they are related to any disciplinary content.

Disciplinary Identification The first level in the disciplinary discernment hierarchy that relies on disciplinary knowledge. A person in this level can identify and name disciplinary objects or concepts within a representation. For example, they may identify that an arrow means force, or that the dots in an astronomy image are stars.

Disciplinary Explanation A person at this level identifies disciplinary meaning with a discerned aspects. This could be that a person recognises why the stars have different colours in a picture of a galaxy, or that the force vector is actually the sum of many forces acting on an object.

Disciplinary Appreciation A person requires a comprehensive understanding of what the semiotic resource represents and can extract this meaning from the representation. The person understands and can evaluate the disciplinary affordances of the semiotic resource.

Disciplinary Evaluation The semiotic resource is evaluated and critiqued based on how it is used and how it may be manipulated. For example, a person in this category may evaluate a semiotic resource based on its affordance and judge how it fits in the current context or situation. They may find flaws in the semiotic resource, or praise how it makes visible specific aspects.[8]

Affordances

Affordance is a theoretical construct that describes what the environment affords an agent that interacts with it. The term was first coined by Gibson (1979) and was used to examine ecosystems and psychology. For example, when a monkey sees a tree, it affords 'climbing' to the monkey. If a fish sees the tree, it will probably not feel an urge to 'climb'. The affordance that Gibson (1979) describes depends on both the environment and the agent that interacts with it. Affordances are thus used to describe what an agent is urged to, or prompted, to when it enters the environment. For example, if a student enters a physics classroom, they should be prompted to learn physics. The environment should be set up in such a manner that affords meaning-making for the student. SS have extracted a subset of all affordances from the environment; The meaning-making affordances. Affordances embedded in the environment, or the semiotic resources, that affords meaning-making for an agent that interacts with them. The meaning-making affordances have been grouped into two separate affordances: *Disciplinary Affordance* and *Pedagogical Affordance* Fredlund et al. (2014); Airey et al. (2014); Airey and Eriksson (2019).

Pedagogical and disciplinary affordances

Pedagogical and Disciplinary affordances are the meaning–making potentials of semiotic resources. Airey et al. (2014) defines disciplinary affordance as:

[8] All descriptions re-phrased from Eriksson et al. (2014).

> “the agreed meaning–making functions that a semiotic resource fulfils for a particular disciplinary community”,

whereas Airey and Eriksson (2019) defines pedagogical affordance as:

> ”the aptness of a semiotic resource for teaching some educational content.”

Thus, disciplinary affordance is related to the disciplinary content that the semiotic resource is designed to convey, whereas the pedagogical affordance is related to how this content is conveyed within an educational setting.

Airey and Eriksson (2019) describes how to move from a semiotic resource with high disciplinary affordance to a semiotic resource with high pedagogical affordance through the application of unpacking, filtering and highlighting, (as described previously). Semiotic resources with high pedagogical affordances can be used as they are, it is only semiotic resources with high disciplinary affordance, but low pedagogical affordance, that needs to be manipulated in such a way to increase the pedagogical affordance of them. Airey (2015) suggests that there exists an inverse relationship between the disciplinary and pedagogical affordances of a semiotic resource. When one decreases, the other increases. The disciplinary and pedagogical affordances can be modified through the act of unpacking, as explored by Volkwyn (2020); Airey and Eriksson (2019); Patron et al. (2021).

Patron (2022) introduces the idea of a *Wave of Affordance*. As a semiotic resource is unpacked, its disciplinary affordance decreases and the pedagogical affordance increases (Airey and Eriksson, 2019). When the semiotic resource is re-packed, that is: the original version of the semiotic resource is reconstructed, the pedagogical affordance decreases and the disciplinary affordance increases. In the process of unpacking and re-packing semiotic resources, the pedagogical and disciplinary affordances will oscillate back and forth in sync like a wave.

Combining them all

All of the theoretical constructs from social semiotics are designed to describe a specific aspect of the learning situation. When analysing the learning situation, each theoretical construct can be applied to their respective area to construct a holistic picture of the learning situation. Semiotic resources and semiotic systems provide a basic description of what is available for the student in terms of the disciplinary and pedagogical affordances. Transformations and transductions describe how these semiotic resources are modified and used by the students. The ADD, combined with fluency and discourse imitation allows us to describe how well the student use, or make meaning, as they interact with the semiotic resources and use it to communicate with each other.

Thus, it is possible to describe what the students are doing, how this appears to affect their learning, and the role of the semiotic resource within this process. Eriksson et al. (2020) further expands SS and suggests that it can be combined with variation theory of learning to create a better tool for analysing and understanding meaning-making in physics.

Variation Theory of Learning

The second theoretical framework that are used in the research presented in this thesis is the*Variation Theory of Learning* (VTL) as described by Marton and Booth (1997); Ling Lo (2012); Marton (1986, 1992, 2015); Marton and Trigwell (2000). The *Phenomenography* part of the framework is not used in this thesis, only the parts relating to students' interaction with representations and their ability to discern *critical aspects* from representations are presented below. Critical aspects are aspects related to the learning goal. Note that Fredlund et al. (2015a) identifies DRAs with the critical aspects in a given learning situation, as they relate to the learning goal of a situation. But critical aspects are also related to overall learning goals, such as learning to write good reports, or create models to analyse ideas. Whereas DRAs are specific to the current learning situation and are disciplinary specific aspects directly tied to the problem at hand. This thesis will mostly focus on the use of DRAs in specific learning situations and how students discern and engage with these DRAs. One of the main concepts of VTL is the idea of discernment of aspects and how this is necessary for learning.

Discernment and learning

Marton (2015) and Marton and Booth (1997) describe how students must be made aware of aspects, if they are to be able to learn them. They have identified that discernment is a necessary first step to learning. For example, if a student is to learn about 'acceleration', they must first discern that acceleration is its own thing, separate from other aspects such as velocity, position, and force. If they can not discern that it is separate, they will not be able to investigate or explore it, preventing any learning about the concept to take place. Another way of thinking about it is; it is not possible to know what 'round' is, if it can not be separated from other shapes. To learn, one must first discern. However, the variation and discernment of concepts must be within the semiotic system and between semiotic systems. A person may discern 'Round' in a pictorial representation, but unable to discern it as a mathematical representation. Ingerman et al. (2009) identified this as variation *within* critical aspects and *between* critical aspects.

Variation

The *Variation* in VTL, is entirely related to making aspects discernible. By varying aspects in a specific manner, they can be made discernible for the student. The specific types of variations that can be used to increase the discernibility are described below. By being aware of the different types of variation the VTL describes, a teacher, or researcher, may use VTL to guide the development of learning environments, see for example Kullberg et al. (2017); Ling Lo (2012); Svensson et al. (2020b).

Patterns of variation

This section draws heavily upon Ling Lo (2012) in the description of the different patterns of variation that VTL uses to describe types of variations.

Contrast By comparing different objects, features that differ between them may be discerned. Contrasting is the act of simultaneously experiencing two instances of an object to discern what differs between them. For example, in Figure 10, both cubes are experienced at the same time and it is possible to discern differences between them. Description based on Ling Lo (2012).

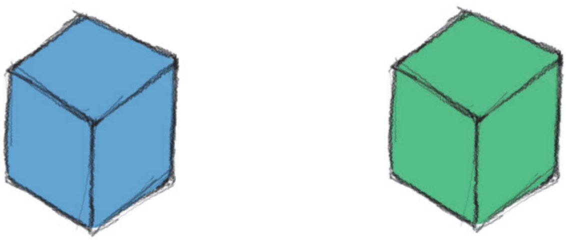


Figure 10: Experiencing two objects at the same time allows for discernment of what differs between them. In this case, the colour of the cube is different and it is possible to learn that cubes can have different colours.

However, only similar objects should be contrasted. If too many aspects differ between two objects, it may not be possible to discern what should be focused on. By only varying the aspect that the student should discern between the two objects, the potential for them to discern it is optimised.

Separation After students have discerned an aspect, through contrasting, they must separate it from the object itself. In Figure 10, the colour is discerned and identified as being separate from the cube itself. It is possible to vary the colour without varying the cube itself. Thus, the feature: 'Colour' is separated from 'Cube'. Description based on Ling Lo (2012).

Generalisation By varying other aspects than the one in focus, an instructor can show how they are separate from the one in focus. This generalises the focused aspect by connecting it to other aspects. In Figure 10 the size of the cubes can be changed, to observe how the colour does *not* change, or light and shadow may be added to see how the colour does change. Generalisation of aspects provides a way to group aspects together by the way they interact with other aspects. Colours will react to light, whereas the size will not. Thus, the observed colours, blue and green, are just different manifestations of 'colour'. 'Colour' is generalised into being understood that it is separated from size, but connected to light and can have different values. Description based on Ling Lo (2012).

Fusion If an aspect is connected to another aspect, they are described as being fused. For example; the area of a circle is directly linked to the radius of the circle through the formula: $A = \pi r^2$. Thus, they can *not* be varied separately, and to fully discern these aspects, they must be examined in unison and their relationship must be discerned. Description based on Ling Lo (2012).

Relevance structure

If a student discerns an aspect, they can start to explore it and use it as a tool to understand the bigger picture. However, the student may not find the aspect *relevant* for the situation and disregard it. In a given learning situation, the discipline has some aspects that it deems relevant, the DRAs. The DRAs are used to investigate, explore, and solve the problem at hand. If the student can discern all the DRAs, and they find them relevant, they have the possibility of solving the problem. However, if they do not discern all DRAs, or they do not find one or some of them relevant, they will not be able to solve the problem.

Thus, there exists two different *Relevance Structures*; The student's relevance structure, as described by Marton and Booth (1997) and the discipline's relevance structure[9]. The relevance structures contains what the student, or discipline, finds relevant for a given situation.

[9] This is not an established separation of relevance structures. But it is a separation that is introduced in paper **VII** and it offers a way of contrasting what the student finds relevant versus what the discipline finds relevant in a given situation.

The aim is to, through instructions, scaffolding, and interventions, make these two relevance structures overlap. It is only when they overlap that the problem can be fully grasped. Figure 11 showcases an example of two relevance structures, one being the discipline's and one being the student's. In the figure, they do not fully overlap and the student's relevance structure needs to be evolved through the use of different interventions, to better match the discipline's relevance structure.

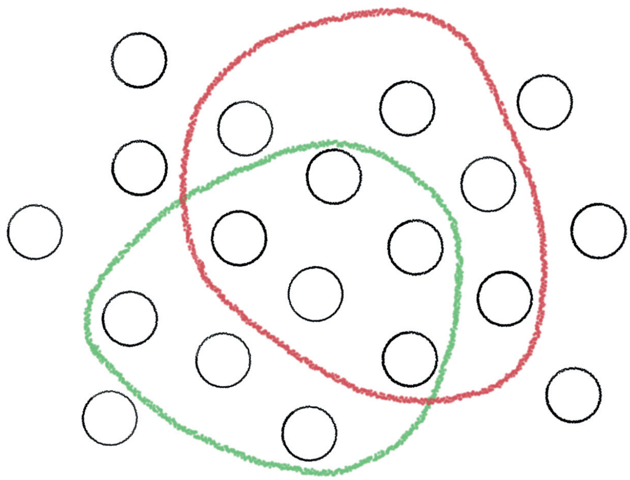


Figure 11: The student's relevance structure (red) does not fully overlap the discipline's relevance structure (green). The teacher must employ a carefully chosen set of pedagogical activities so that the student's relevance structure evolves to match the discipline's.

However, it is not enough to just extend the student's relevance structure to include all of the DRAs. If the total number of aspects in the student's relevance structure is larger than six or seven, the student may begin to struggle to keep them all in their working memory (see e.g., Ma et al., 2014; Paas and Merriënboer, 2020). None–relevant aspects must be pruned from the student's relevance structure as new DRAs are introduced to it.

Methodology

This chapter aims to describe the methodology of the different projects. The chapter begins with the data collection for the different projects and the method used to collect the data. It then explores the analytical approaches used for the projects.

Data collection

Both projects presented in this thesis required qualitative data (Otero et al., 2009) because much of the research were exploratory and aimed at figuring out how different activities were affecting the learning situation and what aspects emerged as important. Based on the descriptions by Robson and McCartan (2016), the data collection presented here, is a combination of *semi-structured interviews* (p.290) and *simulation* (p.362). That is, the data collections are placed within an environment that is designed to evoke some specific learning activities and allow for the collection of data with regards to these activities. Thus, the situation is a simulation that aims to make possible the study of a specific phenomenon. The simulation is structured with tasks and questions for the students to perform. The interviewer guides the students through these tasks by prompts and probing questions. The data collection activities may also be described as stimulated-simulated-participant observation techniques where the interviewer does not distance itself from the interviewee, but may ask probing questions or aim to trigger specific actions in the student. For example, the interviewer may ask the students to draw the concept that they are discussing, or relate it to a known formula. As was done in paper IV. For papers I and II, there were also standard semi–structured interviews that were done in groups as well as individually.

Project 1: Programming as a tool for meaning-making in physics education

To reiterate, the aim of this project was to understand how programming can be used as a meaning–making tool to learn physics. To gain any insight into programming's role in a learning situation, a rich data set was collected. The data allowed for investigation into how students use programming and what being in a programming–environment affords the student with respect to learning physics.

It was decided, through discussions within the LUPER group, that a physics–simulation focused workshop would be offered to upper secondary school students during the spring of 2018. The student group was chosen as it was believed that upper secondary school students would be able to program and explore the simulations, but also that they could reflect on their own experience in a meaningful way. The project was advertised to the students during one of their physics classes and the students volunteered to participate in the study.

The study was designed using VTL as a guiding lens. Programming exercises were constructed to allow for easy variation of different aspects, such as: the variables, shapes, colours, and interactions within the simulation. This allowed me to study aspects that are of interest in the study, such as: how the students visualise their simulations; how they approach the transduction from mathematical model to code–representation.

The study was divided into five sessions where the first four sessions were designed as learning activities and the last session was a series of semi–structured interviews with the students. Each session was video and audio recorded using multiple cameras where three of the cameras were static and one had a small handheld mount so that the camera could be re–positioned to capture any interesting interactions. Microphones where also placed in strategic locations in the room to capture high quality sound. The audio recordings served as backups if a camera would fail. The instructor also wrote down notes and thoughts directly after each session. Paper I goes through the workshop and the programming in more detail and the code for the workshop can be found on Zenodo[10]. In Figure 12, the recording setup is shown for the first session. The setup was modified slightly for each session, depending on the task the students were to perform. All the code that the students produced were also retrieved for use in the analysis. However, the students' code itself did not prove to be useful in the type of analysis performed.

The fifth, and last, session of the programming workshop was dedicated to interviews with each student, as well as a group discussion with all the students. The interview questions can be found in the appendix and the results can be read about in papers I and II. While the interviews were conducted, the other students were provided an opportunity to try out Virtual Reality and they also had some programming-based exercises too keep them entertained. All the data collection took place at Vattenhallen Science Centre at Lund University during the weekends in April and May of 2018.

[10]The code is presented in Svensson (2020a).

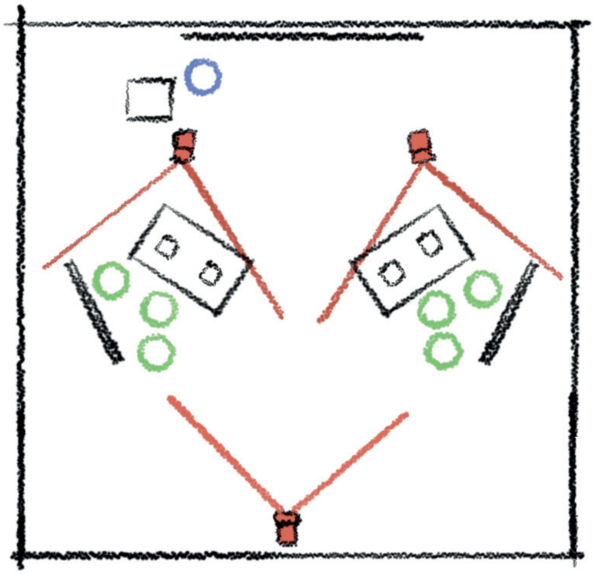


Figure 12: The camera setup for the programming workshop. The instructor live-coded and showcased concepts at the top (blue). The students were divided into two groups (green) where they had access to a whiteboard and computers to code on. The static cameras (red) were positioned to capture the students' discussion as well as the instructor's lectures.

Project 2: Constructing representations for physics education

During the spring of 2021, data were collected that would help to further describe the students' use and construction of semiotic resources in a physics context. However, the data was collected during the Covid–19 pandemic and had to be done remotely. After discussions in the LUPER group and based on input from Bor Gregorcic at UUPER, it was decided that good quality data could be collected using a tool that could record the students' faces, voices, but that also would provide a platform to share and create representations. Zoom™[11] was chosen based on the researchers' previous experience with the software and based on the functionality that Zoom™ provides. The students were also familiar with the software because it was used for remote lectures in their courses.

Discussions between students were recorded in Zoom™ as they discussed concepts related to thermal energy. The data collection relied heavily on Zoom™'s Annotate function to provide a communal area where the students could share and create representations. A PowerPoint was constructed with the interview questions and with the different discussion

[11]Zoom is an online video conferencing software. `https://zoom.us/`

topics. The interviewer shared the PowerPoint using the Share Screen function and asked the students to write and draw the ideas they were discussing using the Annotate function in Zoom™. During the interview session, the audio and video of the entire Zoom™ call was recorded. The students' video was also recorded, however, it was only the thumbnail version of the size the cameras could record. This is a limitation of the Zoom™ setup that was used. However, from the thumbnail data, it was still possible to discern the gestures they used (if the hands were in frame). Figure 13 is a still image from one of the data collection session, without the students' faces, to demonstrate how it looked during the recording. In Figure 13, two students are discussing the task: "How would you describe the concept of Thermal Energy to a classmate?" with the intent to capture the types of representations they use, and how they use them, when trying to explain a concept to a peer. The PowerPoint acts as a background for the interaction and it also prompts the students to use multiple types of representations as they communicate their ideas. The aim was to capture how the students used different representations and to combine this information with the theoretical results from of SS and VTL.

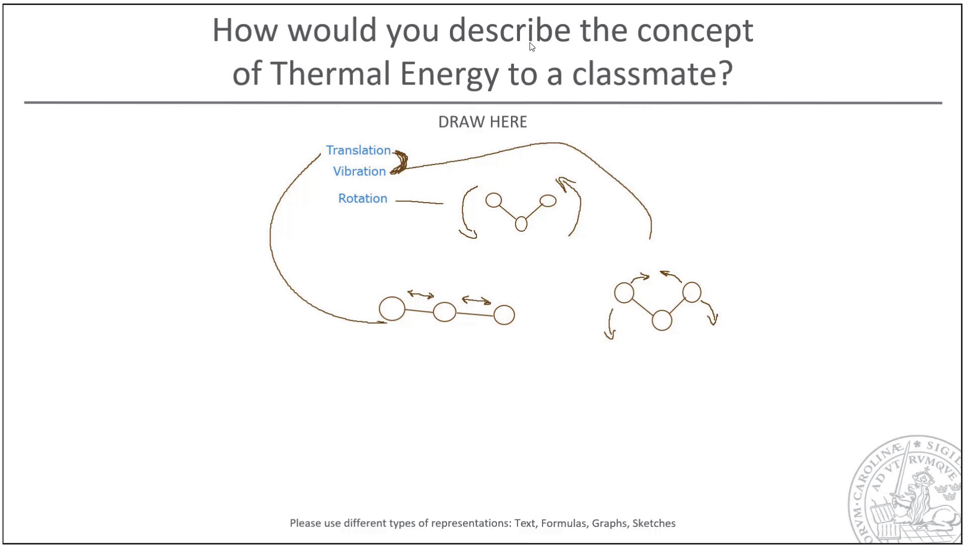


Figure 13: A PowerPoint was shared with the students in Zoom™. The students used the Annotate function to create representations to aid in the communication of the concept of Thermal Energy.

This remote way of collecting data came with some challenges. The biggest challenge turned out to be the students' inexperience in using the Annotate function in Zoom™. Several of the students found using the Annotate function difficult and relied on the other students to write and draw on the PowerPoint. It was anticipated that the student would be inexperienced in using the Annotate function and they were provided with instructions of how to use the Annotate function thirty minutes before the interview started. The students were also invited to the Zoom™ room at the same time with the stated intent that they should familiarise themselves with the Annotate function before the interview started. However, almost none of the students took advantage of the extra thirty minutes before the interview. Some of the students were already proficient, but the ones who had never used the Annotate function before, did not try it out beforehand.

Analysis

The description of the analysis will be presented for each of the different papers. As several of the papers are using the same data, they would not contribute anything new if they also use the same analysis method. Thus, in this section, the analysis is presented on a per paper basis. But first, an introduction to the qualitative approach that is part of all the papers.

Qualitative approach

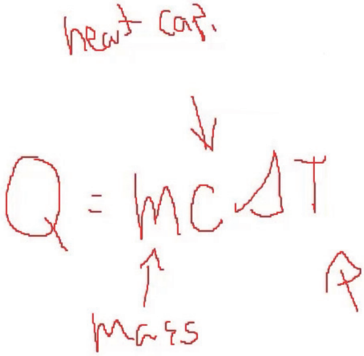
Every paper in this thesis uses the constructs of SS and VTL to describe and identify different learning phenomena in the data. Such as what prompts the student to discern something new, or how a student attempts to communicate with another student. This process involves identifying the semiotic systems, semiotic resources, translations, variations, discernment, student relevance structures, the disciplinary relevant structure, and the affordances of the learning situation. Not all papers use all constructs, but all papers draw from this pool of constructs to analyse the data.

This method is inspired by Grounded Theory (GT) (see e.g., Glaser and Strauss, 1969; Tie et al., 2019). Within GT, the data is coded into categories and from the categories a theory is built that explains the recorded situation. For all papers, the theories have already been decided upon; SS, VTL, and in the case of paper V, the theory of registers of semiotic representations (Duval, 2006). Each theory provides a number of constructs that may be used to describe what is observed in the data. For example, in Excerpt 1 a transduction is identified from 'text' to 'formula' and it can further be described using the ideas of unpacking, filtering, and highlighting, as described above.

The process is the same as in GT. By coding the data, and taking a holistic approach, as well as a detailed approached (studying the data as a whole and in parts), a detailed description of the data can be obtained. As the chosen approach is using already existing frameworks, with predefined constructs, it may be possible to find situations that are not contained within the constructs. In such cases, the frameworks have been expanded upon to include constructs that capture the new situation. This process is exemplified in papers III and IV, where the new constructs; transductive links, transductive chains, active and passive transductions, are defined and used to further describe learning situations in physics.

Excerpt 1: Multimodal transcript from project 2

1	**Fredrik**	We have the formula for heat. [Gustaf nods].. The ’Q’ equals to, what is it, ’mc Δ T’?
2	**Gustaf**	yeah.
3	**Fredrik**	Should I write it down... I can write it down
4	**Kim**	Yes, please do. [Fredrik draws a ’Q’]
5	**Fredrik**	we have ’m’ ’c’ ’Δ T’ [Fredrik draws the symbols as he speaks]
6		[Fredrik writes ’mass’ and draws an arrow from the word ’mass’ to the ’m’ in the formula.]
7	**Fredrik**	’c’ is the.... [Draws an arrow pointing to ’c’] what is this called?
8	**Gustaf**	Heat Capacity...
9	**Fredrik**	It’s called Heat Capacity... Specific Heat Capacity, yeah.
10		[Fredrik writes Heat capacity at the arrow point to ’c’]
11	**Fredrik**	And ’Δ T’ is the, well, change in temperature.
12		[Fredrik draws an arrow pointing to ’Δ T’]



Fredrik writes down the formula for thermal energy, $E = mC_v\Delta T$, but also modifies it by adding arrows and words to explain it. Fredrik unpacks the representation by a transduction between ‘text’ and ‘formula’ and highlights different aspects. The process is a transduction, and from paper IV, is also identified as an active transduction. The transduction provides insight into Fredriks disciplinary discernment.

Paper I: Programming as a semiotic system to support physics students' construction of meaning: A pilot study

Paper I focuses on describing the methodology and the construction of the data collection and how this relates to the ideas of SS and VTL. SS and VTL informed the construction of the data collection and the design of the different programming exercises. The analysis of data is limited and only serves to hint at interesting findings, and paper I states that a deeper analysis of the data is underway.

Paper II: Programming and its Affordances for Physics Education – A Social Semiotic and Variation Theory Approach to Learning Physics

From the extended analysis hinted at in Paper I, SS and VTL are used to identify different aspects of the learning situation. The students' use of programming, but also the act of programming, are examined and described with respect to the meaning–making process using the constructs of SS and VTL. The recorded video and audio were transcribed and constructs from SS and VTL were used to code and fully describe the learning situation. The students' discussions, and how they approached the physics concepts in a programming context, were the main focus in this analysis together with the group and individual interviews. Because the students worked in groups, their approach to programming was captured in their discussions. By interacting with the students, through probing questions, an understanding of how the students desired, or expected, to use programming to implement, examine, and visualise, could be discerned. During the analysis process the students' fluency and intent could be discerned, and from this data the affordances of programming could be constructed. Based on the results, programming is described in terms of what it affords for the meaning-making process; its affordances for meaning-making in physics. The affordances described in the paper may be further understood using the pedagogical and disciplinary affordances and the waves of affordance. However, the waves of affordances construct was only defined by Patron et al. (2021) after paper II had been published and was not used in the paper.

Paper III: Concept of a Transductive Link

Papers I, II, and Airey and Linder (2017, 2009) use the term transductive link to describe a semiotic system that connects two other semiotic systems. However, the term itself had not been defined within the SS literature. Paper III is a theoretical paper that introduces a definition for the term and explores how the definition can be used to better describe the learning situation and how the new construct can be used in the work of planning learning sequences. Thus, the analysis is focused on what the introduction of transductive links, to the SS framework, provides for the analysis of physics education situations, but also what it can provide for the planning of learning sequences. By thinking about why and how to use different transductive links in physics teaching, weak links can be identified and optimised for the situation. The paper further identifies transductive links in previous published research to showcase how the idea of transductive links is not something new, but just a hitherto unknown facet that is present in many different learning situations.

The definition of transductive links was the most critical part of the analysis. The definition was heavily discussed within the LUPER-group and iterated upon a number of times before the final version was settled upon. Once the definition of the construct was in place, the implications of how to use it in research fell into place. By defining the transductive links as supporting semiotic systems in a transduction, gestures, body language, speech, and other non-persistent semiotic systems could be tied to the unpacking, filtering and highlighting of different aspects. This provided a base for identifying transductive links in previously published research, and for describing their role in future research.

Paper IV: Active and Passive Transductions - Definitions and implications for learning

This paper is similar to Paper III, in that it is a theoretical extension of the transduction concept of social semiotics. The paper introduces the constructs of active and passive transductions and analyses them in the same manner as the transductive link construct in Paper III: theoretical examination of the implications of using the new constructs in physics education research, but also an analysis of how the new constructs may impact the planning and execution of learning activities.

Similarly to paper III, it was the definition of the constructs that would prove to be the most difficult. Once the definition was in place, it was mostly a matter of finding useful examples from previous research and connect it to Eriksson (2019) work on disciplinary discernment. As the definition was built upon the constructs presented by Volkwyn et al. (2019), they could be used to connect the concept of transduction to disciplinary discernment.

Paper V: How do students use representations in physics? A comparison of two semiotic perspectives

This paper compares two different semiotic based theoretical frameworks: SS and the TRSR (Duval, 2006; Duval and Sáenz-Ludlow, 2016; Campos et al., 2020). The analysis is two-fold. The first approach compares the theoretical constructs of both frameworks and attempts to identify elements that overlap and where they differ. This can be compared to the comparison performed by Pino-Fan et al. (2015), that compared the Onto–Semiotic approach to cognition and instruction to TRSR, using only an analysis of the same data. Paper V combines the data analysis approach with a the theoretical comparison of the constructs of both frameworks to provide a deeper comparison between the two frameworks.

A secondary analysis emerged during the analysis process. Within the TRSR was a construct that did not exist in SS, namely the idea that there exists at least two different types of transductions (conversions with and without recognition in TRSR). Paper IV was written to include these new types of transductions. Thus, the second analysis aims to describe the usefulness of these type of comparisons between frameworks.

Paper VI: Constructing representations based on Social Semiotics and Variation Theory

The analysis of this paper is still underway and will include SS and VTL. It will use the constructs of SS and VTL to identify important guiding principles for how to construct representations for use in physics education. It will also analyse students' usage of constructed representations, to observe if there are aspects that the frameworks does not account for when constructing the representation.

Paper VII: Dynamics of semiotic resources

This paper's analytical approach diverges from the other papers in that it does not use the constructs of SS and VTL to analyse a learning situation, but it uses mathematics to analyse the constructs within SS. The analysis is based on trying to find a qualitative mathematical description of semiotic resources that can capture how they are used in a learning situation. The analysis employs a number of different mathematical constructs, such as Dual Spaces using the Dirac Bra-Ket notation (Dirac, 1939), and Markov chains (Gallager, 1996). The analysis is basic and only aims to showcase that it is possible to describe semiotic resources using a mathematical framework.

Ethics

All projects presented in this thesis are based on data that participants have volunteered specifically for each project. Each student has had the opportunity to contribute in any manner they want by contacting the researchers, as well as withdrawing their consent at any time.

In the publications, the decision to never show any faces or identifiable information for any of the students was made to future–proof[12] the participants personal information. Even if some of the students agreed to this in the earlier consent forms. Thus, no student is identifiable from the published data. No risks have been identified with participating in any of the projects, except a loss of time on the participants part. However, many participants have stated that it was interesting and valuable to take part in the studies because they got to talk, experience, and think about physical concepts in new ways. Thus, participating in the data collection sessions have often been seen as a positive experience.

Throughout all projects, ethical concerns have been a central part and has informed every decision of the research. Such as, how the research may affect the participants, how it may affect the researcher, how the researcher may affect the participants, and how the resulting publications may affect the participants. Kvale (2007) describes seven stages of ethical issues, in Box 3.1, during a qualitative interview approach. They will now be described and addressed.

Thematizing The purpose of the interview should consider the improvement of the human situation under investigation. Thus, there should be some scientific value to the research, but the research should also be seen as contributing to society in some manner. The research presented in this thesis all relate to understanding and describing the process of learning physics, the results could be applicable directly to improving physics education.

Designing The design of the data collection, analysis and publication should all require the participants informed consent and be designed in such a manner to ensure confidentiality at all stages. This was achieved by following the strict rules of the GDPR (see below), that defines how the participant's data must be handled and the participants rights with respect to the data.

Interview Situation The interview itself may affect the participants through stress, feelings of inadequacy, when in a position of being examined, and recorded by a person of authority. This was addressed by trying to create a relaxed environment and creating a personal connection with the participants through friendly chatter before and after the data collection sessions. The participants were encouraged to inform the interviewer of anything that might be not be correct, or if they wish to redact, change, or add anything to the data collection.

[12]As the idea of personal data and ownership of personal data evolves in society, it was decided that participant faces should never be shown in published research. The statements, gestures, body language, and created representations, may not be something that a participant wishes to be associated with in the future.

Transcription During the transcription, the confidentiality of the participants should be protected. The participants' meaning should also be preserved. Every transcript was anonymised in the process of transcribing the data using fake names instead of the participants' own names. Important aspects from the videos were also added, such as the gestures, facial expression, or other expressions that are not strictly verbal. This ensured a more nuanced view of the situation could be gained, better preserving the intended meaning of the participants. For papers I and II, the data collection was done in Swedish, but relevant data was translated into English. To preserve the participants' intended meaning, they were sent the translated transcripts and asked to comment on the accuracy of the transcription.

Analysis The analysis must be balanced and avoid penetrating the participants' views more than the scope of the research entails. As the research in this thesis does not present specific views or specific understandings of concepts, but instead focuses on how the meaning-making process is performed using semiotic resources, a deep analysis does not go into the participants' own views. The analysis in papers II, III, IV, V, and VII, instead aims to study the theory and tools required for meaning-making.

Verification The findings and interpretations should be verified and accurately represent the data. In every stage of all papers, the LUPER-group have provided input on interpretations, biases to be aware of, what can be interpreted, from the data. This is combined with established methodologies and theoretical frameworks, such as SS and VTL, to ensure a unified base on which conclusions can be drawn.

Reporting The reporting of the findings should consider the ramifications of the participants. This is handled by complying with the GDPR with respect to the handling of the personal data of the participants of each project. In the GDPR-compliant consent form and information sheet, the participant is informed how the results of the data collection will be presented to a wider audience and they must accept this to participate in the study. It was also decided early on that no traceable information would be published with respect to the participants.

Ethics committee

In Sweden, there is no requirement to obtain an ethics approval from the Swedish Ethical Review Authority unless sensitive information is processed, as defined by the Swedish law (2003:460), which aligns with section 9.1 of The General Data Protection Regulation ((EU) 2016/679). Which are stated as follows (translated from the Swedish Ethical Review Authority webpage: `https://etikprovningsmyndigheten.se/` accessed 2022-02-

21). The data collected is sensitive if the purpose of the data collection is research and that the data collection

- involves a physical intervention, either on an alive, or diseased person,
- uses a methodology that aims to affect a human being physically or psychologically, or presents an obvious risk to the participant, or
- is performed on biological matter, from either living or diseased persons, and is traceable.

Based on the Swedish Ethical Review Authority and Swedish law, it was decided that there is no needed to seek ethical approval for any of the research presented in this thesis.

GDPR

The General Data Protection Regulation ((EU) 2016/679) (GDPR (2018)) came into effect on the 25th of May, 2018. This was in the middle of the data collection of the first project. Thus, the consent form that the students signed for the programming project was not compliant with the GDPR. However, the students were updated in the new regulation and their rights with respect to their own data and the data is managed in compliance with the GDPR.

A not insignificant portion of the PhD has gone to understanding the GDPR and designing consent forms and data collections that comply with the GDPR, together with Moa Eriksson. As well as guiding fellow researchers in the LUPER-group in this process. Thus, all data collection after the first project was done with GDPR compliant information sheets and consent forms, as well as the actual data collection itself.

Results

In this chapter the results from the two projects: *Programming as a tool for meaning-making in physics education* and *Constructing representations for physics education* are presented. The results are only summarised and the reader is referred to the different papers for a more thorough results section. The chapter ends with a section on the trustworthiness of the results.

Project 1: Programming as a tool for meaning-making in physics education

Project 1 was designed with the aim to investigate programming as a meaning-making tool for use in physics education. The analysis was done using SS and VTL as the lenses.

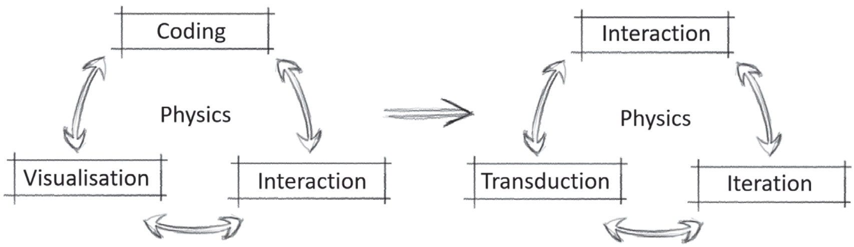


Figure 15: The results are represented in the image above. Through interaction with the code and visualisation the student may iterate upon their model. The movement between model, code, and visualisation, is facilitated using transductions which (may) require the student to unpack, filter, and highlight aspects of the concept. Figure from paper II.

The expected results from the project was that the interaction between the code, the visualisation and the interaction with the visualisation would be the driving force of the programming experience. As seen in the left image in Figure 15. This was updated when the analysis had been done and different aspects could be clumped together and described in the transduction concept (right image in Figure 15). The ability to iterate using the instant feedback was also identified as being an important part of the learning experience.

Results from papers I and II

Programming is identified as its own semiotic system. Programming is a qualitatively different way to represent physical ideas. Thus, it is a new way of expressing and experiencing physical concepts.

Programming is identified as a transductive link. The concept of a transductive link is further explored in paper III and programming is used as an exploratory example.

In paper II the affordances of programming for physics education are identified. The affordances are: programming's ability to act as a transductive link between many different semiotic systems; the ability to vary aspects in accordance with the variation theory of learning; the iterative process that allows the student to explore ideas and concepts.

Physics is also identified as an especially good match with programming, as both disciplines use logic and mathematical expressions to represent different concepts.

The physics student requires, at least, an introductory course in programming to be able to modify the code based on their own ideas.

Paper III: Concept of a Transductive Link

Paper III was also a result of project 1. However, it falls outside of the aims presented for project 1. The aim for paper III was to define and develop the new theoretical construct: transductive link, and show how it may be used in PER to better describe the learning situation. The basic idea of transductive links are not new and have appeared before, but under different names. Stein (2008) calls the idea *Chains of semiosis* and the term transductive link was used by Airey and Linder (2017). The concept of transitional representations have also been identified in mathematics education research (Duval, 2006; Campos et al., 2020; Rahmawati et al., 2020).

Figure 16: Programming can be viewed as the semiotic system that facilitates the transduction from, in this case, formula to graph. Figure from paper III.

Figure 16 showcases an example of a transductive link: programming. On the left side, we have the semiotic system 'Formula' and on the right side is the semiotic system 'Graph'. They are connected using the transductive link 'Programming'. The transductive link affects the transduction process by altering the semiotic material.

Results from paper III

Transductive links are identified as its own construct that exists to support the movement of semiotic material from one semiotic system to another semiotic system.

Transductive chains are introduced as a means to describe how several semiotic systems are used in series; As a chain of transductive links.

The conservation, and modification, of semiotic material is identified as one of the corner stones of transductive links.

Learning sequences can be planned and expressed using the idea of transductive chains.

Project 2: Constructing representations for physics education.

Project 2 is not officially complete, as the main output, paper VI, is not complete. However, the data from project 2, was also used in papers IV and V. The results from those two studies are presented below.

Paper IV: Active and Passive Transductions - Definitions and implications for learning

Paper IV presents the following results with respect to the introduction of the theoretical concepts of Active and Passive transductions. In Figure 17 the ADD is connected to *shown engagement*. Active and passive transductions may be placed within the graph, depending on how much shown engagement the student displays. In the figure, a student must have a minimum level of disciplinary discernment to be able to show engagement when performing a transduction. Thus, the larger the shown engagement, the higher up the disciplinary discernment hierarchy the student must be.

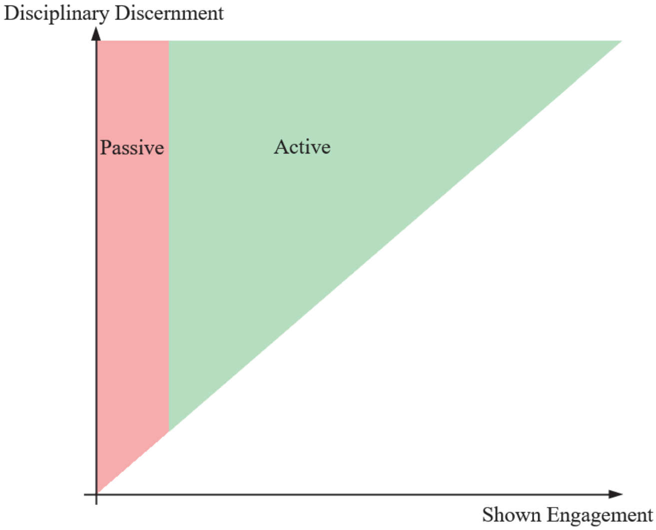


Figure 17: Shown engagement is connected to disciplinary discernment and passive and active transductions exemplifies this connection. To show engagement in a transduction, the student must have some disciplinary discernment. Figure from paper IV.

Results from paper IV

The identification and definition of active and passive transductions.

The connection between shown engagement while performing transductions to the anatomy of disciplinary discernment.

How to identify active and passive transductions in the physics classroom and how to use this information to guide interventions.

How active and passive transductions can guide the construction of assessment tools.

The term *shown engagement* is defined using the ideas of unpacking, filtering and highlighting and is inspired by Volkwyn et al. (2019).

Paper V: How do students use representations in physics? A comparison of two semiotic perspectives

Paper V compares the two semiotic based theoretical frameworks: social semiotics and the theory of representations of semiotic registers. Figure 18 showcases the overlap between the different constructs of both theories that overlap with each other.

Results from paper V

Many of the constructs within social semiotics and the theory of representations of semiotic registers overlap and may be used together.

Comparing different theoretical frameworks with each other may reveal gaps in their respective descriptions. Paper V is a direct result of this comparison.

The main difference is the social and cognitive aspect. Social semiotics describes meaning–making in social situation and the theory of representations of semiotic registers describes the manipulation of representations from a cognitive perspective.

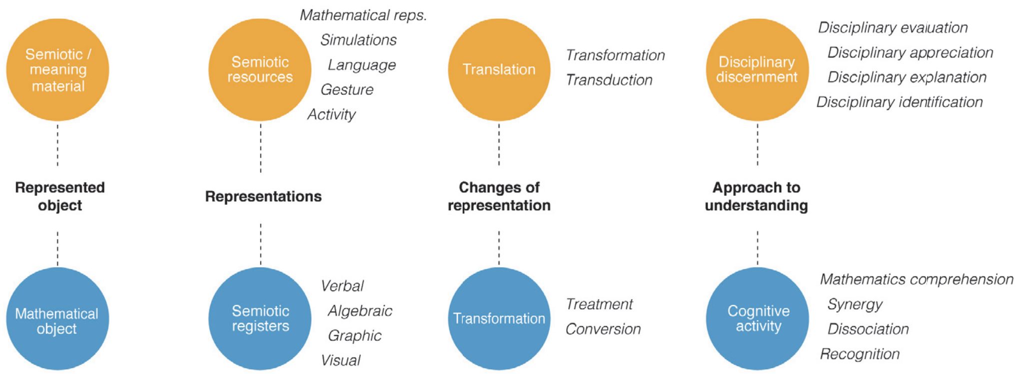


Figure 18: Theoretical constructs from the theoretical frameworks of social semiotics (top) and the theory of representations of semiotic registers (bottom). Many of the constructs overlap and both frameworks identify the same aspects as relevant, such as moving between verbal and mathematical representations.

Paper VI: Constructing representations based on Social Semiotics and Variation Theory

The data is still being analysed and no results will be presented here.

Paper VII: Dynamics of semiotic resources

As paper VII has been a side project during most of the PhD, the results of it are separate from project 1 and project 2. Paper VII presents a mathematical toy model of semiotic resources and identifies structures found in the mathematics with observed phenomena in the meaning–making process.

Results from paper VII

It is possible to construct a mathematical model of semiotic resources using the idea of a Dual-Space.

Transformations of semiotic resources can be modelled as operators operating on the Dual-Space.

The Dual-Space is spanned by Disciplinary Relevant Aspects and Discernible Aspects.

Student Disciplinary Discernment is measured by: $\langle L|\, S\, |R\rangle$

The learning goals, $\langle L|$, are identified with the DRAs (mirroring the findings of Fredlund et al. (2015a)).

Markov-chains are used to model the student's discernment of aspects in a learning situation.

An embedded Markov-chain is identified with the student's relevance structure.

The idea that interventions can be modelled as changes to the student's relevance structure (embedded Markov-chain), by changing the discernibility of DRAs.

Trustworthiness

One of the largest difference between *soft* and *hard* science is the ability to ensure that your results can be trusted. Established methods exists in the physics discipline that can be applied to sort, extract, and manipulate data, all of which can be replicated if provided with the same data. The only argument that may arise is if the assumptions used are applicable to the current situation. However, in PER, a researcher must argue for, not just the assumptions, but also for the chosen methods and how the results are interpreted.

Thus, I will now argue for the assumptions, methods, and the results for each project in this thesis.

Project 1: Programming as tool for meaning-making in physics education

The arguments here relate to papers I and II, the intent of the project was to study programming itself; how programming could be used as a tool to learn physics.

Assumptions The first assumption is the idea that programming can be used to learn physics, or to investigate and explore ideas from physics. This assumption comes from personal experience and is based on observations from a programming workshop a Vattenhallen Science Centre. The second assumption is that it is possible to observe the process of learning and point to aspects that affect the learning process. This assumption is addressed using the theoretical frameworks of SS and VTL, that together provide a framework for analysing students' use of representations, and by extension, programmings role in the construction of representations and its role in the meaning-makiing process.

Methodology The methodology of the programming study aimed to capture qualitative data and to extract meaningful aspects from it. Video and audio recordings were used to capture the students' discussions and their code was collected to be used in the analysis. The qualitative data afforded interpretations of the transcripts using the lens of SS and VTL. The methodology was guided by "*how* programming could be used..." and a quantitative method would not provide data to answer this question.

Results The results from the project are interpretations of the data by the research team at LUPER. The interpretations are done using predefined constructs from SS and VTL, and the interpretations are done together with other experts in the field. Thus, an expert in the theoretical frameworks would probably end up with similar results. Not exactly the same, because the results are coloured by the person interpreting them, but the overall structure and conclusions would align with each other. The claims from papers I and II are also modest and do not go beyond what the data or the theory can say.

Project 2: Constructing representations for physics education

The arguments here relate to paper VI, and the intent of the project was to obtain insight in how the theoretical frameworks of SS and VTL could be used to guide the construction of representations for use in physics education.

Assumptions The biggest assumption for this project is the idea that there exists some type of unified underlying structure of representations that can be accessed through observations and theory. The argument for this comes from all other different representational disciplines, such as advertising, comics, graphic design, and similar. Where unified rules for how colours complement each other, shapes, action lines, focal points, and more have been constructed to encompass all types of representations (Pridmore, 2021; Fogelström, 2013; Cohn and Maher, 2015; Thon and Wilde, 2016). Thus, there may be some underlying rules that governs the semiotic aspects of the representations. Rules that either draw upon, or expand, the rules established in other representational disciplines. The construction of representations have also been addressed previously in educational research, see for example: Tytler et al. (2007); Ainsworth (2006); Prain and Tytler (2012); Ainsworth et al. (2011); Tytler et al. (2013). However, constructing representations using SS and the VTL, have not been fully explored.

Methodology The methodology is guided by the aim of the project: to construct a set of guidelines for creating representations for physics education. The first step is to understand the theoretical frameworks of SS and VTL with respect to what they say about representations. This involved a focused literature study and discussions with experts on semiotics and representations. The second step was to collect data were students use and construct representations. This data was collected using the Zoom™ video conferencing program due to the Covid-19 pandemic. By comparing the theoretical constructs from SS and VTL, to how students actually use and construct representations, it is expected that a set of guidelines can be constructed to help instructors construct new representations for use in physics education.

Results The project is still ongoing and the guidelines have not yet been formalised.

Comparing theoretical frameworks

This study overlaps with project 2, because they use the same data set, and the data collection for project 2 was influenced by this study. The result of the study is paper V.

Assumptions The assumption of this study is that the two theoretical frameworks of SS and TRSR can be compared. This comes from the basic idea that they both draw upon the idea of *Semiotics* (see e.g., Joseph, 2012; Peirce, 1998) and that they are applied in very similar situations, such as describing the student's usage of representations to learn mathematics and physics concepts.

Methodology The project uses a two-pronged approach. The first is a purely theoretical comparison of both frameworks. Idea by idea are compared between the frameworks to see if they overlap. The second is a comparison of the results that emerge from applying the frameworks on the same data. The two-pronged approach provides a varied and exhaustive data set and analysis.

Results The results of this study showcases that there is a need to perform comparisons between theoretical framework because the act of examining the framework from a different perspective provides insight into further development of the frameworks. As exemplified by paper IV. The results are reliable because they are derived both from a theoretical perspective, but also from empirical data.

Developing transductions

Papers III and IV emerged from project 1 and 2, but they are unrelated to the original aims of the projects and they need to be addressed by themselves.

Assumptions The assumptions for both papers is that SS is not a fully developed framework and can be further developed by examining empirical data. Other authors (e.g., Eriksson, 2019; Airey and Linder, 2009; Linder, 2013; Fredlund et al., 2015a, 2021; Patron et al., 2021) have added new constructs to the framework in order to expand and make it more useful for the PER field. This showcases that the social semiotic framework is far from complete, but also that its current constructs may be used to build more advanced ideas.

Methodology The first step was to establish if the current theoretical constructs that exists within SS could be used to explain the observed phenomena. When it was determined that no construct could be used to explain the phenomena, a definition for the new construct was iterated upon together with experts at LUPER and UUPER. From the definition, further implications were found, such as the connection to the ADD in paper IV.

Results By building upon previously established ideas from SS and published research (Airey and Linder, 2009, 2017; Volkwyn et al., 2019), the ideas presented in papers III and IV, have a firm foundation. The results follow from trying to explain empirical data using established theoretical frameworks, and the need to introduce new definitions to fully capture the observed phenomena.

Modelling semiotic resources

This was a side-project that started during project 1 with the aim to better understand semiotic resources by modelling it using mathematics.

Assumptions The largest assumption for this project is the idea that there is a way to compare different semiotic resources with each other in a meaningful way, such as comparing a text to an image with respect to their meaning-making potential. The multifaceted way of knowing from SS encapsulates that it is possible, and desirable, to experience the same concept by using different semiotic resources. There exists some similarity between the semiotic resources that allows them to point to the same concept, but at the same time, the semiotic resources are different entities. Thus, there could exist some way of describing the similarities and differences, in terms of the aspects, that a semiotic resource affords a learner.

Methodology A mathematical approach was chosen to describe semiotic resources. This approach was chosen to better ground this new description of semiotic resources in some established framework. The first step was to establish a mathematical description of semiotic resources that captures the essence of the concept, as described by SS. The second step was to manipulate the mathematical description, interpret the results, and tie them to observed learning phenomena. Using the rules of mathematics, together with observed phenomena and theoretical constructs from SS and VTL, a connection between the mathematical dynamics and the observations was found.

Results It turns out that it is possible to describe and compare semiotic resources using a mathematical framework. The established frameworks of SS and VTL allow us to identify structures that emerge from the mathematical formulation. This is an indication that there is some congruence between the mathematical model and SS and VTL. However, it should be noted that the model can not make predictions at this time and should be seen as a mathematical toy model that aims to capture the essence of semiotic resources and how they are used in physics education.

Guba and Lincoln, and high quality social research

The author would like to acknowledge the work done by Guba and Lincoln (1982), who introduces the notion of high quality social research. They introduce four quality assurance check marks that mirror hard science's process of establishing high quality research; *Credibility*, *Dependability*, *Confirmability*, and *Transferability*. However, the four qualities will not be expanded upon further in this thesis because they are addressed in the various papers. Each paper has its own way of satisfying the different categories. However, each paper is not explicit in how they are tackling the different categories, but they are implicitly addressed through the descriptions of the theory and methodology. Below is a breakdown of how the different areas have been addressed.

Literature review Search for literature to understand what has been done before with respect to the specific field or concept that is under investigation. The literature search has been guided by experts and structured using digital tools, such as Mendeley[13]. However, the literature review was not systematic but employed searching google scholar, physical review, European journal of physics and other journals, for relevant articles.

Expert discussion Discussions with experts to figure out problems or to be advised with regards to: gathering data, analysing, organising, writing, and interpreting the data. The discussions took place at every stage of each project; from the initial idea to the submission of the papers. The experts were some of the leading experts in PER in Sweden that had some connection to LUPER and UUPER. Because the chosen frameworks were SS and VTL, frameworks that LUPER and UUPER have developed expertise in during the years, there has not been a need to seek expert council outside of this group. However, sporadic discussions and seminars with Prof. Russell Tytler[14] and Dr. Emily Patron[15] have proven enlightening. This constant discussion and investigation ensured that many different perspectives were part of each step, removing the author's individual bias to a certain degree, but also introducing new and varied ways to think about the projects.

[13]A reference handling program used to organise literature, such as books, articles, and proceedings. `https://www.mendeley.com`

[14]Professor of Science Education at Deakin University

[15]Lecturer at Linnaeus University in Sweden

Established methodologies The projects' use established methodologies to gather, handle, analyse, and present the data. However, as research is about exploring new frontiers, the methodologies have been applied in situations were they have not been used before. Such as in paper II where SS is used in the analytical process of describing students' interaction with programming. When problems with the methodology, such as when the analytical tool was not enough to adequately describe the situation, they were expanded upon to further develop the analytical process, which can be seen in papers III and IV.

Pilots and tests For every project, pilots or tests were designed to ensure that the methodology would work to produce high quality data to be used in the analysis. These tests or pilots could be in depth discussions with other experienced researchers that had done similar data collections, or drawn from experience, such as the programming project that had its pilot in a science centre. The equipment, or procedure, was tried with experts that had knowledge of the project, such as the data collection using Zoom™ (papers IV, V, and VI), to find flaws, biases, or strengths of the methodology that could be harnessed. The PowerPoint, for the data collection of project 2, was tested with interested participants and adjusted based on their feedback before it was deployed to collect data.

Participant feedback Each participant has, as part of the data collection, been encouraged to reflect back on the study to provide feedback about the data it has captured: Does the data represent what *You* (as a participant) want to say? What have we (the researchers) missed? What could change? The participants were also encouraged to contact the researchers about any questions they had with regards to the project. However, only one participant has actively reached out after the data collection was completed.

Discussion

This chapter aims to discuss the results presented in the previous chapter. The discussion presents the underlying idea and the development of the concepts explored in this thesis. It starts by discussing the affordances of programming (papers I and II) and how the exploration of these ideas spurred the exploration of transduction (papers III and IV) and a mathematical description of semiotic resources (paper VII).

I, the author, will also inject personal experience and interpretations of the results and how I believe they could be developed in the future.

The affordances of programming in physics education

The aim of studying programming in a physics context was to examine what programming affords for the meaning-making process in physics education. If programming affords the same, or worse, meaning-making compared to other learning activities in physics education, there would be no need to include programming as an meaning-making tool. However, if it affords a new way to make meaning, a new way to explore or experience a physics concept, it may be fruitful to explore as a new tool in physics education.

Papers I and II, explores this question using a simulated learning situation together with semi-structured single and group interviews. A workshop was constructed with the intent to put a group of upper secondary education students through a number of programming and physics related tasks. Each task was designed to provide the student with some insight of how programming may be used to model a physics concept, and the tasks were structured to allow them to explore the concepts using variation of aspects as described by VTL.

Code-along

The introduction of programming was done using a *code-along* method, where the lecturer coded a physics engine live, and the students followed along on their own computers. The code-along method is based on Daniel Shiffman's[16] method that he uses (Shiffman, 2019), whose popular YouTube™ channel teaches programming using the code-along method. It is also the code-along method that is used in the workshop at Vattenhallen Science Centre and for the data collection in project 1. The code-along method was chosen because of personal experience in employing the method in the science centre programming workshop, and I had personally enjoyed the method when learning new programming concepts.

However, the code-along method was not evaluated with respect to other methods, such as: Pair-Programming (Williams, 2001; Nosek, 1998) or Flipped Classroom (Låg and Sæle, 2019; Fung, 2020). The code-along method for data collection was deemed adequate for the research situation. It was also combined with other group-based activities such as group discussions around planning the code and modelling of physical systems. The student groups all had access to paper, pens, and whiteboards, to allow for the spontaneous creation of representations. The setup can be seen in Figure 12, where the lecturer guides the students by coding and projecting the code on a projector-screen.

I would now, with the experience and knowledge I have gained during the PhD, argue that the choice of using a code-along was probably one of the best way of introducing programming to the students. The code-along method meshed very well with active learning and the group-based tasks in an efficient way during the data collection. An argument could be made that I also used a version of Pair-Programming during the data collection, because the students worked in smaller groups to create, implement and explore models of physical concepts.

Visualising code

Visualising is a part of programming, or simulating, different physical concepts. The visualisation can be in the form of a list of numbers, a graph, or an animation, and serves the purpose of highlighting, or gathering, some output from the code that is difficult, or even impossible, to discern from the code itself. The visualisation is thus separate from the code, but also intrinsically tied to it.

[16]Associate Arts Professor at the Interactive Telecommunications Program at NYU's Tisch School of the Arts and host of The Coding Train on YouTube™ `https://www.youtube.com/c/TheCodingTrain`

The process of visualising

The student must decide what aspect is relevant to highlight in the visualisation. Hence, the student's choice of visualisation will be directly tied to their *enacted relevance structure*, as described by Euler et al. (2020). The student's choice of aspects to visualise specific aspect can be used to obtain knowledge of what they discern and what they find relevant. This knowledge can then be used to create interventions that address possible errors in the student's reasoning.

As described in papers I, II, and III, the act of visualising the simulation, requires a transduction from code to visualisation, and, as explored by Volkwyn et al. (2019), transductions provide the opportunity for unpacking, highlighting, and filtering of the semiotic material. However, as explored in paper IV, a transduction does not necessitate that the unpacking, highlighting, or filtering are enacted by the students.

The first step the student must do, when visualising a simulation, is to choose a variable to tie to a visual cue. The cue could be a shape, colour, line, text, or number. It can also be tied to emergent properties of the simulation. For example, a student may be interested in the shape a galaxy takes when simulating it. The shape of the galaxy is not stored in a variable in the code, it is an emergent property based on the dynamics of the implemented model. The student must then identify variables that are indicators of the emergent phenomenon, such as the density of gases, or position of stars. The act of identifying which variables are relevant requires imagination combined with disciplinary knowledge.

In Figure 19, a hanging cloth simulation is visualised in different ways depending on what aspects should be highlighted. In the figure, the left-most visualisation highlights the underlying structure of the simulation: it uses particles attached by springs to simulate the cloth and the particles are shown as red disks and the springs are shown as black lines between the particles. The middle visualisation aims to show the larger dynamic shapes of the cloth, such as the wrinkles on the right hand side. The right-most visualisation shows the size of the net-force of each particle. Each visualisation provides access to a separate disciplinary relevant aspect. Figure 19 is just a single frame of an animation and the system is not in equilibrium, producing an image of the cloth that may look strange.

Interactive visualisations

The physics engine, that was constructed for project 1, allowed for interaction with the visualisation using mouse and keyboard. The interaction with the simulation afforded the students the opportunity to explore ideas about the simulation. This can be seen in Excerpt 2; the students are exploring a simulation of hanging cloth that the researcher provided. Their task was to come up with a model that could simulate hanging cloth and were provided with a simulation that they could use as inspiration. In the excerpt, the students are using their observations from interacting with the visualisation to evaluate their own theoretical model that is yet to be implemented. In Figure 19, the middle visualisation accurately captures the simulation the students interacted with.

Figure 19: Different visualisations of a hanging cloth simulation. Each visualisation provides discernment of different aspects. Each of them are based on the same simulation, but they are visualised differently.

When a visualisation has been created, the student may start to discern new aspects by exploring and interacting with the visualisation. When they have discerned an important aspect, or failed to discern it, the student may go back to the code to change something to produce a new visualisation. The student may enter a feedback loop where each iteration through the loop allows the student to further explore the simulation.

Positive feedback loop

As the student constructs models, writes code, and visualises the simulation, they have the possibility of entering into a feedback loop. By interacting with a visualisation, as seen in Excerpt 2, the students could compare it to their theoretical model. The interaction with the visualisation acted as a way to explore the simulation and by extension, their own ideas about the simulated system.

Interaction with the visualisation prompted a transduction from visualisation to abstract model. Figure 20 demonstrates the different transductions that should occur when using programming as a tool to learn physics. The possibility to perform transductions between the code, the visualisation, and the abstract model, provides the foundation for a loop to take place.

Excerpt 2: Students interacting with cloth simulation

1	**S4**	Can you throw the curtain above?
2	**S1**	What?
3	**S4**	... is it possible to throw the curtain up completely?
4	**S1**	But it can go down, than it does not work if we can pull it down.
5	**S4**	Can you pull it down?
6	**S1**	It can be pulled down more than it is.
7		[S1 uses the mouse to drag the curtain downwards.]
8	**S1**	It can move down.
9	**S4**	That is a bit strange, maybe.
10	**S2**	Yes, but that would work here too if all [the particles] move.
11	**S1**	But, then it does not work...
12	**S2**	It can still work, they still move freely so that means that if they are on the sides from the start, they can move downwards.
13	**S1**	Eeh.

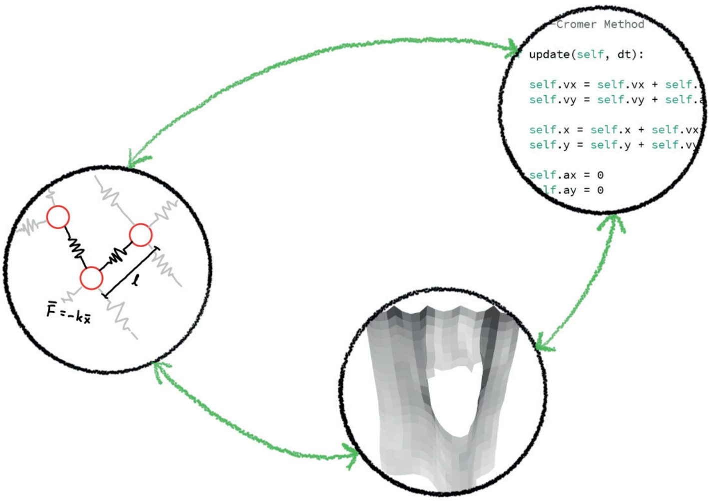


Figure 20: The learning process using programming; the transductions between the abstract model, the code representation, and the interactive visualisation, produces the foundation for a feedback loop.

However, to prompt the student to perform the transductions, they need a moment of realisation. This could be as simple as making an error in the code, observing the error in the visualisation, and realising that they need to change something in the code, or it could be a profound realisation that they now have a new aspect to investigate. As seen in Excerpt 3, the student recognises that the instant feedback is valuable for their ability to investigate their code.

Excerpt 3: Instant feedback

1	**S1**	What I thought was good was, within physics, is... when we have worked, with forces, you have to think a little extra when implementing them into code... what directions. The good thing is that you get instant feedback if you've... if you've done it correctly or not.

If the feedback is delayed, the student's focus may be elsewhere. For example, if a student receives feedback hours, or even days, after they came up with an idea, or asked a specific question, they may not be in the same head space, nor have the same focus or interest, that they had when the idea occurred. However, if the feedback is quick, almost instant, the train of thought of the student may still be related to the initial idea that they are investigating.

With the, almost, instant feedback provided by programming, the student is given the opportunity to expand on their thought's and delve deeper into the idea. I call this the *positive feedback loop*[17], and it is the combination of the possibility of a feedback loop and the instant feedback, that makes it a positive feedback loop. The *positive* part encapsulates that meaning–making has a high chance of taking place when the student is engaging with the feedback loop and the semiotic material being manipulated by the student is preserved during the different transductions.

Programming and physics

The physics discipline investigate physical phenomenon by finding specific aspects that may provide some insight into the phenomenon. These aspects are related to the phenomenon according to some rules; the laws of physics. The laws, theories, and ideas, that underpin physics are described using mathematical formulas and mathematical ideas. This is how the physics discipline has chosen to represent ideas about the physical world. This representation has proven to be efficient and useful for investigating the real world. When a

[17]The name "positive feedback loop" is not final and will probably change when a deeper study is made into the feedback loop itself.

physicist comes across a new phenomenon, they attempt to create a representation that can capture the essence of the phenomenon at hand. For example, the formula for Hooke's Law: $\bar{F} = -k\bar{x}$, only describes an ideal spring, or the essence of what a spring is. It does not capture how the springiness changes with temperature, the fatigue of the spring after heavy use, air resistance, and many more factors. The intent of the representation is aimed at representing an essential part of the spring and physicists may use the representation to investigate that specific aspect of springs.

In programming, the aim is also to find a way to represent the idea, or concept that you aim to implement. This representation includes everything in the code and the visualisation itself. The code is structured in a manner to capture the essence of the phenomenon under investigation. For example, a for-loop may be employed to iterate the simulation over time. The important time aspect is captured by a structure in the code – the for-loop. A list of numbers can be used to represent a grid on which the simulation can take place.

Both programming and physics draws upon the idea of creating a representation that can capture the idea of a phenomenon and both disciplines use concepts from mathematics as core ideas in their representations. This unified grounding means that it is often unproblematic to move from a simple physics formula to a code representation of the same formula. For example, in Figure 21, Newton's law of gravitation is represented both in mathematical and code form. Both representations are very similar in their structure and the same aspects are highlighted using the same colour in both representations.

$$\bar{F} = \frac{gMm}{|\bar{r}|^2}\hat{r}$$

```
Fx = g*M*m/(r*r)*dx
Fy = g*M*m/(r*r)*dy
Fy = g*M*m/(r*r)*dz
```

Figure 21: Mathematical representation (top) and code representation (bottom) of Newton's law of gravitation. The different aspects are colour coded and match each other in the two representations. Both representations are similar and this similarity makes the movement between the two representations smoother.

Examining the representation

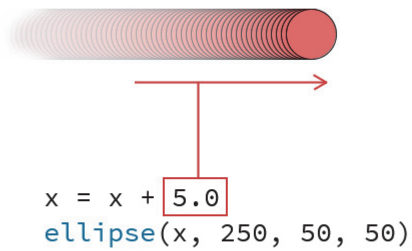


Figure 22: A red disk moves to the right. The movement started when the `x = x + 5.0` was added to the code (red square). The observed motion must thus be produced by the added code. The second line of code draws a circle at position `(x, 250)` in the window.

In Figure 22, a red disk is moving from left to right when the program is run. When the line '`x = x + 5.0`' was added to the code, the disk began to move across the screen. Thus, somehow, the aspect of velocity, or motion, is encoded in the new line of code. It should be noted that this code runs each frame of the simulation. After observing the change in the visualisation, the student must now try to understand how this visual change is related to the change in the code. There is a duality between the visualisation and the code representation. By examining one representation, the student can gain insight into the other representation. In Figure 22, the student must realise that `5.0` is added to the x-position each time the disk is drawn, changing its position. The next step the student must realise is that `5.0` represents a change in position and that a change in position can be related to velocity by $\Delta x = v\Delta t$, where v is the velocity and Δt is the time step. With this, the student can put ideas together and potentially say that `5.0` = $V\Delta t$. This realisation opens up a new venue of investigation; *"What happens if I change the velocity?"; "What happens if I make the time step negative?"*

Students must realise the duality between the code and the visual representation and that a change in one representation is the result of a change in the other. Thus, if a new phenomenon emerges in the visualisation, such as 'motion' in Figure 22, that phenomenon is encoded in the change to the code. By exploring the code, the abstract model, and the visualisation, the student may discover how this phenomenon emerges and how it relates to other aspects of the simulation. VTL describes this as a fusion of the two aspects, a change in one will produce a change in the other. The two aspects, the code, and the visualisation, are linked.

Expanding transductions

This section is connected to papers III and IV, and is a discussion about the theoretical development of the concept of transduction. The development of the transduction concept is based on observations during the data collection sessions (and analysis) of project 1, but also on the comparison of semiotic frameworks captured in paper V. From the analysis of the data, it became clear that further development of *how* transductions are used and described were needed to better capture and describe the observed learning situations.

The first development was to define the concept of a transductive link (paper III) and the second was to subdivide the transduction concept into active and passive transductions (paper IV).

Transductive links

In paper III, the theoretical construct of a transductive link is defined as:

> *"A transductive link is any semiotic system that supports the transduction process between two different semiotic systems."*

The definition is constructed to be wide in its application but precise in its description. A semiotic system is only a transductive link when it supports a transduction. However, the support may be manifested in basically any way. For example, I identify programming as a transductive link in papers I, II, and III, because programming supports the movement of semiotic material from abstract model to visualisation. Programming supports this transduction in the largest sense – the semiotic material moves fully through the semiotic system of programming. Programming captures the full scope of the transduction.

However, a transductive link does not need to have a massive effect on the transduction. For example, imagine a lecturer moving from a formula to a graph on the whiteboard and uses gestures and speech during the transduction, the gestures and speech are transductive links. Both semiotic systems are supporting the transduction and helps to either highlight, filter, or unpack, the semiotic material as part of the transduction.

A transductive link is not part of the initial or final semiotic system of the transduction, but plays an important role while experiencing the transduction. Transductive links are transient phenomena; they are only invoked during the transduction.

Different transductive links will affect the transduction differently. Using programming as a transductive link is different compared to using gestures and speech, even if the overall transduction is the same: formula to graph.

Using transductive links to describe the learning situation

The reason for introducing the construct of transductive links in paper III was to better describe the role that programming fills in the meaning-making process. Programming is a tool that is used to move from, for example, a formula to a visualisation. Thus, the term transductive link aims to better describe the role of programming in the learning situation.

When used to describe the learning situation, the researcher is given access to information of the role of the different semiotic systems that are in use. One semiotic system is identified as the initial semiotic system, one is set as the final semiotic system, and some may be identified as transductive links. The role of the semiotic systems identified as transductive links is immediately clear and a deeper understanding of the learning situation is gained.

However, to further add detail to the description, the researcher need to add *how* the transductive link is used to affect the transduction. Thus, the researcher should state that gestures are used as transductive links between formula and graph by highlighting how x is the same in the graph and the formula. By describing how the transductive link is used, using the three aspects of Volkwyn et al. (2019), a more nuanced and informative description of the learning situation is obtained.

Transductive chains

As a lecture progresses, several transductions will be made, often from the final semiotic system of a previous transduction. The previous final semiotic system becomes a stepping stone to another semiotic system, it becomes a new transductive link that is connected to the previous transductive link. Several transductive links connected in a chain is called a transductive chain (Svensson and Eriksson, 2020). Figure 23 shows this concept in picture form.

Figure 23: Several transductive links are combined to create a transductive chain.

With a transductive chain comes the natural metaphor of finding the weakest transductive link. As the semiotic material flows through the transductive chain, being transformed as it passes through each link, some links may be pedagogically weaker compared to other links. That is, links in which the semiotic material is confuscated, distorted, or in other ways transformed in such a way that it is hard to discern the relevant aspects for the student.

By identifying the weak links in the transductive chain, they can be replaced by links that are better suited for the situation. A teacher should have the option to introduce different transductive links, depending on which link the student is fluent in. The transductive links should be chosen to capture the disciplinary content, but also the student's ability to use the semiotic system being employed as a transductive links.

Imagine a scenario where the students are currently talking about a concept (the semiotic material). The student has several potential transductions that they may perform – they may decide to draw a picture, or a formula, or a graph, based on their discussions. They will, hopefully, move to another semiotic system, and when they are using the new semiotic system they have a new choice: where to go next? In Figure 24, a series of potential transductions between different semiotic systems are shown in grey. From the different semiotic systems exists several potential transductions, creating a web of potential transductive links. A transductive chain is highlighted in green, and should be interpreted as the links that have been chosen to move from the initial semiotic system to the final semiotic system. The single transductive chain is the realised transductive chain, amongst a web of possible transductive chains.

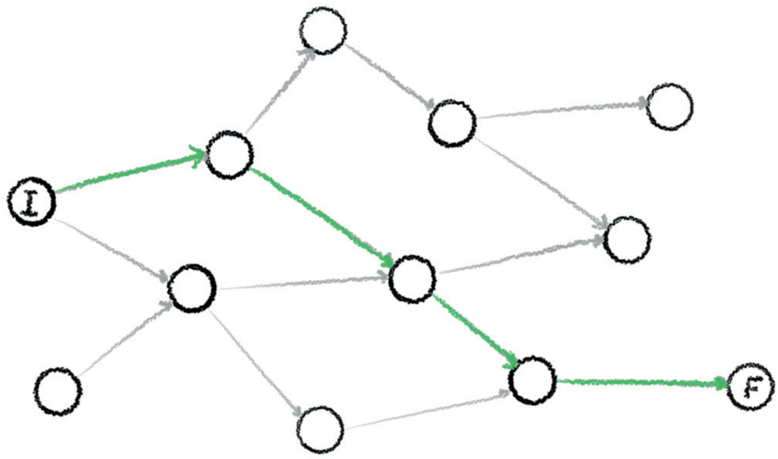


Figure 24: A web of potential transductive links connects different semiotic systems. A chosen specific chain is shown in green that connects the initial (I) semiotic system and the final semiotic system (F).

Different paths through the transductive web afford different opportunities for meaning-making as the semiotic material is represented in different semiotic systems. Thus, to improve the meaning-making, the teacher may change the links they use, but they may also change the path they take through the transductive web. The path through the transductive web should depend on the specific disciplinary content under consideration, but also the students' fluency within each semiotic system. It may be possible to represent the concept as a tensor, but if the student is unable to discern any disciplinary relevant information from the tensor, it should not be chosen.

Within the transductive web exists some fixed representations that all chains will move through. For example, the formula $F = m\bar{a}$ is a representation that all physics students will experience and engage with as they learn physics. Thus, a transductive chain that presents the concept of force, will move through that specific representation. By finding these fixed nodes in the transductive web, the web may be reduced from a web growing in all directions to a set of fixed nodes that needs to be visited as part of the chain.

Active and passive transductions

The second addition to the transduction construct is the identification of *Active* and *Passive* transductions. Paper IV defines the different types of transductions as:

> **Active Transduction:** *The student shows engagement with the semiotic material during the transduction.*
>
> **Passive Transduction:** *The student does not show engagement with the semiotic material during the transduction.*

The definitions are based on how the student performs the transduction and how an observer interprets the transduction. This is different when compared to transductive links, that does not depend on the student or an observer. Active and passive transductions are based on a concept I have chosen to call *Shown Engagement*.

Shown engagement

In paper IV, *Shown Engagement* is defined as:

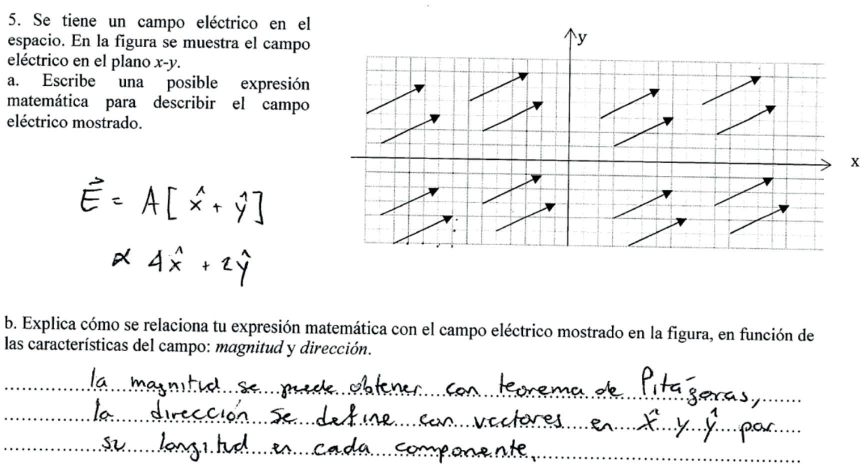
> *Students play an active role in the unpacking, filtering, or highlighting of aspects in the transduction.*

Which should be interpreted as: do you, as an observer, see the student take part in any of the activities related to performing a transduction: unpacking, filtering, or highlighting. Thus, if a student is not displaying that they engage with these actions when performing a transduction, the transduction is a passive one.

However, a student may still perform these actions as part of the transduction, but they are not showing it. The transduction is still passive, because the observers can not tell what the student is doing. A passive transduction gives no insight into the student's engagement with the semiotic material, and thus, from that specific transduction no assessment can be made regarding the student's disciplinary discernment.

Unpacking, filtering, and highlighting are all tightly coupled to the semiotic material that captures the disciplinary content of the situation. However, transductions may be performed without considering the semiotic material. In Excerpt 4, a student is solving a problem involving electric fields. As part of the solution, the student performs at least one transduction, from text (5.a) to a mathematical description. However, at no point does the student actually engage with the semiotic material itself. The student's solution is purely a mathematical one, but the content is based on physical concepts. Thus the transduction in Excerpt 4 is passive but it also showcases that the exercise itself may not be useful to evaluate student understanding. It is possible to solve the exercise without any physics knowledge nor engaging with the disciplinary content, only mathematical knowledge is required to analyse the diagram and to write a formula that describes it. The very nature of the exercise makes a passive transduction likely and probable for the student to perform. The student has no need to unpack, filter, or highlight aspects with respect to the physics to solve the problem.

Excerpt 4: Passive transduction from paper IV[18]



5. Se tiene un campo eléctrico en el espacio. En la figura se muestra el campo eléctrico en el plano *x-y*.
a. Escribe una posible expresión matemática para describir el campo eléctrico mostrado.

$$\vec{E} = A[\hat{x} + \hat{y}]$$
$$\propto 4\hat{x} + 2\hat{y}$$

b. Explica cómo se relaciona tu expresión matemática con el campo eléctrico mostrado en la figura, en función de las características del campo: *magnitud* y *dirección*.

la magnitud se puede obtener con teorema de Pitágoras, la dirección se define con vectores en $\hat{x}$ y $\hat{y}$ por su longitud en cada componente,

Figure 25: The task given to the students in Spanish.

Translated into English:

5. There is an electric field in space. The figure shows a part of the electric field in the x-y plane.
a. Write a possible mathematical expression to describe the electric field shown.
b. Explain how your mathematical expression relates to the electric field shown in the figure, in terms of the features of the field: magnitude and direction.

The student answered:

a.

$$\vec{E} = A[\hat{x} + \hat{y}]$$
$$\propto 4\hat{x} + 2\hat{y}$$

b. *"The magnitude can be obtained using the Pythagorean theorem, the direction is defined with vectors x and y and by the length of each component."*

Disciplinary discernment

To be able to unpack, filter, or highlight, aspects of the semiotic material as part of a transduction, the student must be able to discern and manipulate those aspects with respect to the discipline and the context they are currently in. The theoretical construct of disciplinary discernment by Eriksson (2019) describes this competency and the ADD can be used to assess the student's potential of engaging with the representation. In Figure 26, the relationship between shown engagement and disciplinary discernment is shown as a graph. The shown engagement depends on the students disciplinary discernment level. The higher up the student is in the ADD, the more engagement they have the potential to show. Thus, if a student shows a large[19] amount of engagement during the transduction, it can be assumed that they have a high amount of disciplinary discernment.

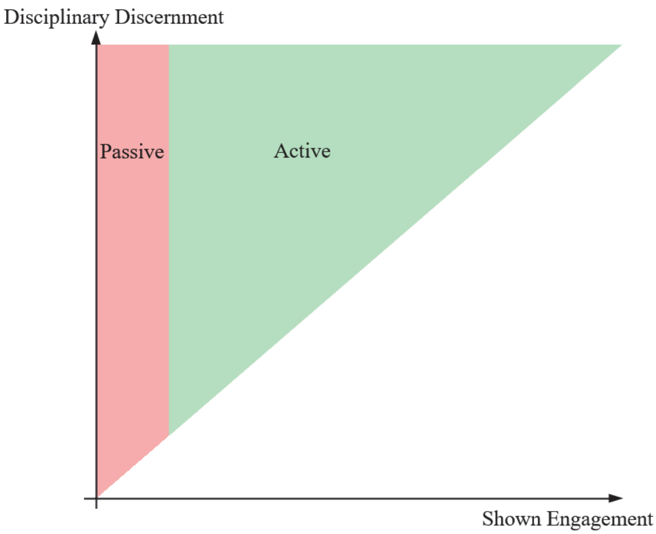


Figure 26: A graph that shows the qualitative connection between shown engagement and disciplinary discernment. The student can only position their transductions within the coloured triangle; the student requires some level of disciplinary discernment to be able to show engagement during a transduction.

If a student performs a passive transduction, nothing can be said about their disciplinary discernment. Notice that the red, passive, area in Figure 26 covers the whole disciplinary discernment axis. Thus, if the student performs a passive transduction, no insight can be gained into the student's disciplinary discernment level. To assess the student's disciplinary discernment, using their usage of representations and transductions, the student must per-

[19] I have not defined how to grade shown engagement. However, I believe it is possible to find a good gradation of shown engagement by looking at how the student unpacks, filters, or highlights, different aspects during the transduction.

form active transductions. Assessment tools, such as exams, must be designed to prompt the student to perform active transductions, such that the student is forced to engage with the semiotic material in an explicit manner. The exercise in Excerpt 4 is a bad exercise for assessment because the student may complete the exercise without performing active transductions.

Too much active transduction

If all the exercises the student engages with, is forcing them to perform active transductions, the student may be overwhelmed by the amount of work they are expected to do. Active transductions require more time to perform and they require the student to examine their own thoughts about the transduction they are doing. *Cognitive Load Theory* (Paas and Merriënboer, 2020; Chandler and Sweller, 1991), tells us to avoid extraneous cognitive load that may hinder or interfere with the learning process. If the student is forced to perform active transductions all the time, the active transductions will contribute to the extraneous load (Paas and Merriënboer, 2020), which will impact their ability to learn.

An exercise, or assessment, should focus on making just a few, specific transductions active. The active transductions should focus on what the exercise is teaching, or what the assessment is assessing, and other aspects of the exercise can be kept passive[20]. The student will spend extra time, and focus, on the important aspects of the task, and less time on the other aspects.[21]

Semiotic comparison

This section discusses the findings of paper V. The aim was to gain new insights into semiotic based theoretical frameworks by comparing two different frameworks that uses semiotics as their basis. The idea emerged during an online discussion with Dr. Esmeralda Campos. During the discussion she introduced the TRSR framework and explained some of the constructs of TRSR, and connected them to ideas from SS. The discussion sparked the idea that it could be useful for the PER community to compare the two frameworks to establish when and how each framework should be used, and even if they could be used together. Another potential effect of the comparison was to find areas in each framework that may be underdeveloped and to develop them further. A similar comparison was done by

[20]Note that the idea of active and passive transductions may also be extended to cover all types of translations. However, the implications for this has not been examined and only active and passive transductions are presented here.

[21]However, I have not done research into how to construct these type of exercises, tasks, or assessments, and can not argue that they are simple to construct, or even possible. Nor have I had time to search the literature on the construction of assessments to see if this is already common knowledge.

Pino-Fan et al. (2015) using TRSR and another framework: The Onto-Semiotic approach to mathematical cognition and instruction. Our approach to the comparison is similar to the approach taken by Pino-Fan et al. (2015); analyse the same data using both frameworks and compare the process, and the results, of the analysis. The analysis in paper V also includes a comparison between the different theoretical constructs of each framework to further add depth to the comparison.

Before the analysis, and the results, are presented from the comparison, the central ideas of TRSR must first be introduced. However, as this is not a framework that I use on a daily basis, the introduction will be a short overview and I will refer the reader to paper V (or to Campos et al., 2020), where a better description of the framework is presented by Dr. Esmeralda Campos.

The Theory of Registers of Semiotic Representations

TRSR (Duval, 2006) is a theoretical framework focused on studying meaning-making within the discipline of mathematics, but has been applied in disciplines where mathematics plays an important role, such as physics (Campos et al., 2020). The framework has identified a number of important constructs that are used to describe a student's use of mathematical representations and the frameworks ties this use of representations to the student's mathematical comprehension. One of the core ideas of TRSR is also that the mathematical objects that are represented does not have a physical representation. That is; the concept under investigation does not have a physical representation, but is purely mathematical, or abstract, and needs to be represented in some register, such as the verbal register, or the written register.

Theoretical constructs

In Figure 27, which is the same as Figure 18, many different constructs of TRSR, and SS, are presented and connected. The figure is the result of analysing the different constructs from both frameworks and identifying how they describe the same underlying phenomenon during the learning situation. It was encouraging that both frameworks identified the same phenomena during the learning situation as important, indicating that the phenomena is real and not a figment of the specific lens that one framework employs to study the situation. (They could still be figments of the larger semiotic framework, but in that case, they could be called features of semiotics.). Such as the movement between different types of representations. In TRSR, this movement is called conversion and in SS it is called transduction.

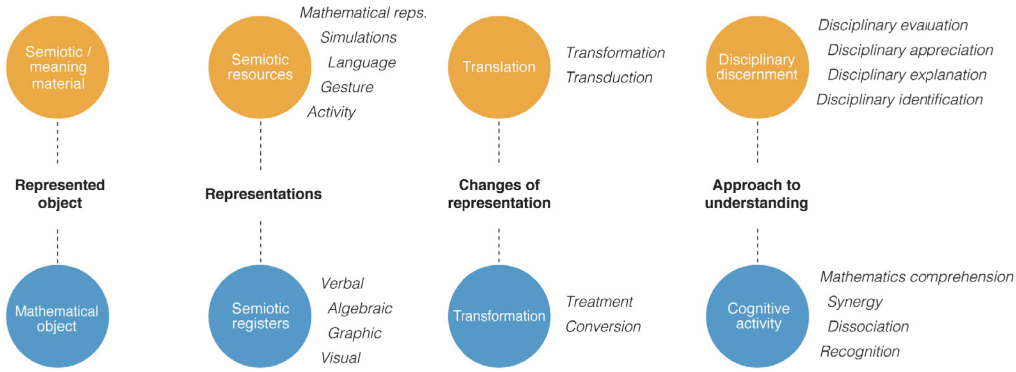


Figure 27: Theoretical constructs from the theoretical frameworks of social semiotics (top) and the theory of registers of semiotic representations (bottom). Many of the constructs overlap and both frameworks identify the same aspects as relevant, such as moving between verbal and mathematical representations. Image created by Dr. Elias Euler for paper V.

From Figure 27, it can be argued that it is possible to move between the different frameworks during the analysis of learning situations and that an analysis carried out using one framework can be compared to an analysis in another framework. However, to do the conversion between the two frameworks, a researcher needs to be well versed in both, as each construct can not be converted one-to-one. One construct in SS may be a combination of several constructs in TRSR, or vice-versa.

Paper V does not describe how this conversion should be made, as that treatment would result in another full paper and require further analysis. I can only argue that it may be possible and that a path forward where both frameworks may be employed in the same study to bring more depth to the analysis may exist.

Analysis approach

Both frameworks, TRSR and SS, were used to analyse the same data. The analysis identified the same phenomenon of the student's use of representations to discuss, solve, and communicate physics. During the analysis, it became clear that both frameworks operate in almost the same manner when performing the analysis: identify phenomena that can be described using the different constructs, build a holistic picture of the situation by taking into account the context and the full interaction when examining details.

Differences

In the analysis, it became apparent that TRSR had not been applied to live conversations between students and that this was a new potential source of insights. One new aspect that emerged was that treatments and conversions, from TRSR, could be triggered by other students as part of a discussion. They did not need to be contained to a single student's use of representations, but could be considered as a part of a communication between students, or as a result of an interaction between students.

In SS, the focus is the construction of knowledge in a social setting, using semiotic resources. Thus, it is inherently tied to the communication between peers and the process they use to communicate. SS is used to study the use and the dynamics that occurs when students use semiotic resources and it is difficult to apply to static situations without knowledge of the construction of the representations. For example, SS would not be my first framework to evaluate exams because I would not have access to the process the student used while constructing the representations. Whereas TRSR may be used to evaluate static representations.

Development of frameworks

The biggest immediate result from the study was the realisation that these types of studies can help to further develop each framework by the identification of constructs or ideas that are present in one framework, but not the other. One such aspect was the identification of active and passive transductions and the creation of paper IV. One of the transductions that prompted the development was the transduction shown in Excerpt 4. The excerpt clearly depicts a transduction, but is also devoid of any unpacking, filtering, or highlighting of relevant aspects.

Another idea that is in the works is the introduction of a direction of transductions. A transduction from A to B is not the same as an transduction from B to A. An idea that is present in TRSR but not in SS. Physical representations may also be included in TRSR (Campos et al., 2020), as well as including communication and having group-wide conversions and triggers for conversions. However, these ideas are still just ideas and have not been explored yet.[22]

[22]This is because of time constraints. I am writing this thesis instead of exploring these ideas.

Mathematical description of semiotic resources

The main idea that went into paper **VII**, was to find a way to compare semiotic resources with each other in a meaningful way. It ended up as a mathematical framework that can be used to describe some of the meaning-making phenomena that are observed when students interact with representations. The most important idea was the realisation that to compare two different semiotic resources; I had to find a basis in which both semiotic resources could be expressed. This was found by looking at the meaning-making potential, or the affordances, of the semiotic resources. This is captured in the Dual-Space system of discernible aspects and disciplinary relevant aspects.

A very important note for this section: this is a toy model that was developed as a side project during the PhD to try to satisfy a nagging question of how to compare a formula to an image from a meaning-making perspective. Paper **VII** presents the current state[23] of the model and in this section I want to address some problems of the model and how and when it may be useful to adopt ideas from it.

Discernible aspects and DRAs

A central feature of the mathematical model is the duality between discernible aspects and DRAs. Discernible aspects are what can possibly be discerned from a semiotic resource and DRAs are the aspects the student should discern. Fredlund et al. (2015a) identifies DRAs with the critical aspects of VTL, and are closely mapped to the learning goals for the learning situation. However, critical aspects span a larger set of skills and aspects compared to DRAs, but they overlap within smaller focused learning environments. The discernible aspects and the DRAs should match. That is: the semiotic resource should allow for discernment of aspect that matches the learning goal of the situation. Mathematically, this is represented as

$$\langle \mathrm{L}|\mathrm{R}\rangle = \mathrm{k}, \tag{3}$$

where $\langle \mathrm{L}|$ is the DRAs, or the learning goals, and the $|\mathrm{R}\rangle$ is the semiotic resource with its discernible aspects, and k is a measure of how well they overlap. This allows us to represent different semiotic resources using the same basis. In theory, it is now possible write out everything a book affords to discern, and the same may be done for an image. As the same basis is used to describe all semiotic resources, they may now be compared in this basis.

[23]As of the writing of this thesis, paper **VII** has come back from review and will be expanded upon to make it clearer and more understandable, but the core idea will remain the same.

Measurement problems

Readers familiar with Paul Dirac's bra-ket notation from quantum mechanics (Dirac, 1939) may be jumping to conclusions about the structure of $\langle L|$, $|R\rangle$, and k. In quantum mechanics, we often normalise the states such that the measurement represents a probability of finding a specific outcome. This can be done because we have a conserved quantity that can be tied to the operation – probability[24] – that can not go above a specific value.

If normalisation were imposed on k, or the states $\langle L|$ and $|R\rangle$, it would imply that there exists some conserved property when comparing semiotic resources, or even a conserved property when discerning aspects from said semiotic resource. This is not something I am comfortable claiming because a statement like that would have severe implications for learning and using semiotic resources to learn.

Another important aspect of k is that it is probably not a normal number. When operators are introduced to the model, such as the student, k represents how much the student has discerned from a semiotic resource with respect to a specific learning goal and from Eriksson (2019), disciplinary discernment can be categorised in a hierarchy. k is a measure that captures this hierarchy. There is currently no known way to measure k in a quantitative manner. However, through the ideas described in paper IV, it might be possible to connect the ADD to what a semiotic resource affords.

Operators and students

To measure the student's disciplinary discernment, they must be introduced into the model in some manner. This is done using operators. The student is represented as an operator that interacts with the semiotic resource:

$$S\,|R\rangle = |R_S\rangle\,. \tag{4}$$

Where $|R_S\rangle$ represents what the student together with the semiotic resource, or specifically what the student discerns from the semiotic resource. This must now be measured with respect to the DRAs, or the learning goals:

$$\langle L|\,S\,|R\rangle = \langle L\rangle\,R_S = k_S, \tag{5}$$

[24]QM assume that a particle may be found somewhere and in some instances the probability may go above 1, allowing us to, potentially, find two particles.

where k_S now represents the student's disciplinary discernment with respect to a specific learning goal as they interact with a specific semiotic resource. k_S should be interpreted as capturing where in the ADD-hierarchy (Eriksson, 2019) the student is located.

Modifying semiotic resources

By using operators, modifications of semiotic resources can now be described. The operators changes the discernible aspects of the semiotic resource. The main title of my licentiate thesis was: "This pen is a rocket", together with a version of the sketch shown in Figure 28 (Svensson, 2020b). In Figure 28, a person says "This pen is a rocket" to another person and holds up a pen. The act of holding up the pen and making a statement changes what is discernible from the semiotic resource. The second person in the sketch is not only interacting with the pen, but also the statement, the gestures and the body language of the other person (gestures have been shown to help with the learning and understanding of different concepts, see e.g., Kang and Tversky, 2016; Valenzeno et al., 2003; Matlen et al., 2012):

$$\mathrm{SBL}\,|\mathrm{Pen}\rangle = \mathrm{S}\,|\mathrm{Pen_{BL}}\rangle\,. \tag{6}$$

In Equation 6, the other person S is interacting with the new semiotic resource $|\mathrm{Pen_{BL}}\rangle$ which is different from the semiotic resource $|\mathrm{Pen}\rangle$. The operators B and L captures the body language and the statement of the first person. The statement, gestures, and body language add new discernible aspects to the pen relating rockets. The second person is thus more likely to discern rocket-like aspects from $|\mathrm{Pen_{BL}}\rangle$ compared to $|\mathrm{Pen}\rangle$.

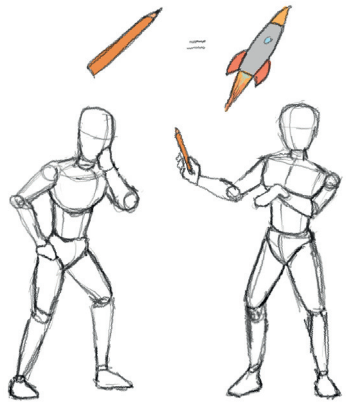


Figure 28: As the right person says "This pen is a rocket", rocket related aspects will become more discernible for the second person.

Using the idea of operators to model modifying semiotic resources allows for further examination different operators, or different ways to modify the semiotic resources. Learning activities may be modelled as modifications to semiotic resources together with the student operator. For example, the order of the operators can be changed and when the student interacts with the semiotic resource can be adjusted. One such learning activity is Flipped Classroom (see e.g., Låg and Sæle, 2019; Lage et al., 2000; Finkenberg and Trefzger, 2019) that is used in physics classrooms where the student interacts with the material before going to meet the teacher. In the model, the order of operators can be explored using the ideas of commutators:

$$\mathrm{FS}\left|\mathrm{R}\right\rangle - \mathrm{SF}\left|\mathrm{R}\right\rangle = [\mathrm{F}, \mathrm{S}]\left|\mathrm{R}\right\rangle . \tag{7}$$

In the flipped classroom case, there appears to be a difference in the learning outcome when the operators are flipped:

$$\left\langle \mathrm{L}\right| \mathrm{FS}\left|\mathrm{R}\right\rangle - \left\langle \mathrm{L}\right| \mathrm{SF}\left|\mathrm{R}\right\rangle = \left\langle \mathrm{L}\right| [\mathrm{F}, \mathrm{S}]\left|\mathrm{R}\right\rangle \neq 0. \tag{8}$$

The notion that the order of operators can affect the students disciplinary discernment can be used as a tool for optimising a learning sequence. By modelling a learning sequence as a long list of operators that acts upon the semiotic resource, the order of different operators can be changed to obtain different outcomes. Thus, in theory, learning activities can be optimised by changing the order of the operators, with regards to the student's possibility for disciplinary discernment. However, as the student operator S is part of the chain of operators, each optimisation is personal to that specific student. Each student is different and this means that each student operator must be different.

Relevance structure

By building on the idea of discernible aspects, a learning situation may be described as a large collection of discernible aspects. Some of the discernible aspects are relevant and connected to the learning goals of the activity. The student will move through this collection of aspects, discerning one aspect and then moving on to discerning another aspect. Eventually, the student will settle into moving between a smaller number of aspects that the student has judged to be relevant for the situation. The set of aspects that the student moves between is situated within the larger set of discernible aspects of the learning environment. The student's subset of discernible aspects can be identified with the student's relevance structure (Marton and Booth, 1997). By analysing which aspects the student discerns and which aspects they move between, an understanding of their relevance structure can be gained. Figure 29 showcases the discernible aspects and the student's relevance structure.

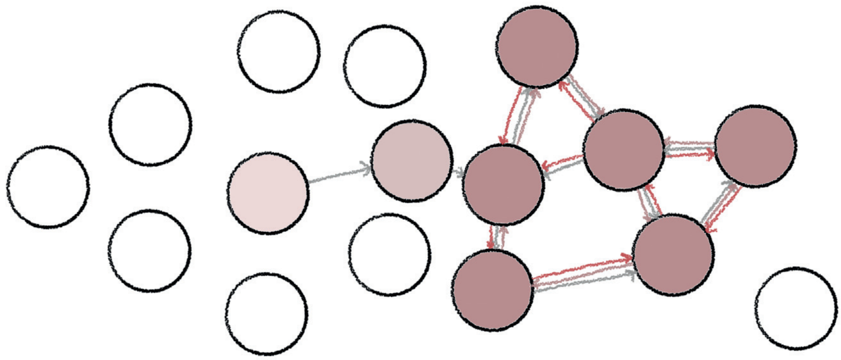


Figure 29: Discernible aspects (circles) and a subset that the student is moving between (dark red). The student's relevance structure is defined by the discernible aspects that the student choose to move between.

Figure 11, combined with the ideas in Figure 29, points to the introduction of interventions to the model. Interventions would be aimed at making specific aspects discernible for the student. But not just discernible, they should be shown too relevant for the situation so that they may enter into the student's relevance structure. Interventions are thus modelled as modification of semiotic resources that first make specific aspects discernible to the student, but also show how the aspect is relevant to the situation.

Translation and transductions

In reality, a learning situation is not just a bunch of disembodied discernible aspects. The aspects are clumped into different semiotic resources. The space of discernible aspects is divided into a smaller number of semiotic resources. Figure 30 showcases an example of this division where the discernible aspects are divided into three different semiotic resources. These semiotic resources will overlap with each other in terms of the discernible aspects they contain. As the student moves between different aspects, they may stay within the same semiotic resource, or they may move to another semiotic resource. Movement between different semiotic resources should only occur when the two semiotic resources have some discernible aspects in common. For example, if a graph shows the magnitude of a velocity, the next semiotic resource used should also allow for the discernment of the magnitude, such as a vector representation of the velocity.

The idea of staying within the same semiotic resource may sound like it is related to the translation from SS. However, the mathematical formulation deals with student's discernment of different aspects within a semiotic resource. The same may be said with the transductions concept and moving between semiotic resources. However, manipulations of the semiotic resource that keeps the student's focus within the same semiotic resource may be identified as a translation and manipulations or interventions that moves the student from one semiotic resource to another may be identified as a transduction. In Figure 31 the idea of moving between discernible aspects within a semiotic resource and between semiotic resources are shown.

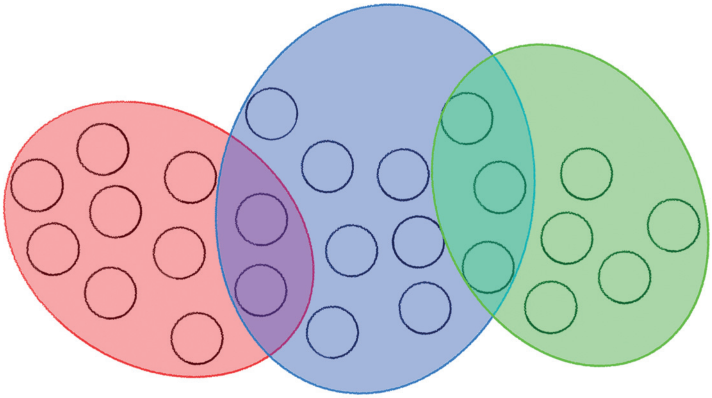


Figure 30: The discernible aspects (black circles) are situated within a set of semiotic resources (coloured disks). The semiotic resources overlap, which means that some aspects are discernible in several semiotic resources.

This use of the terms translation, transduction, and even semiotic resource, is different compared to how they are used within social semiotics. In social semiotics, the terms all tie their existence to the construct of semiotic systems. However, I have not found a need to introduce semiotic systems to the mathematical model, nor has a structure emerged within the model that could be identified with semiotic systems. The mathematical usage of the terms translation and transduction captures the essence of the terms as they are used in social semiotics, but they are not a perfect representation of the ideas.

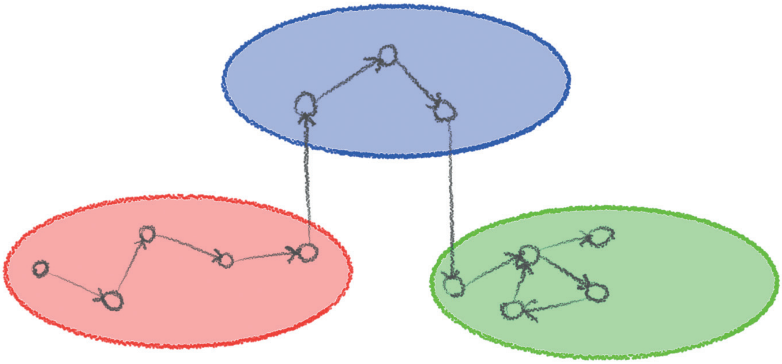


Figure 31: Three semiotic resources with discernible aspects. The student moves between discernible aspects within each semiotic resource and between semiotic resources. Movement between semiotic resource should only occur when two semiotic resources discernible aspects overlap.

Development of related ideas

Much of the ideas discussed above have been developed through discussions with others, especially Pendrill (2022), who have taken the ideas in her own direction and applied it to modelling interventions. In the paper, Pendrill is proposing a mathematical structure, using matrices, to model interventions. The paper models interventions as matrices that move student from one outcome to another, and with a series of interventions, aiming to achieve that the outcome of the student body converges to a single answer – the correct one.

Conclusions

The research began by studying programming in a physics education context. The aim was to find out if and how programming could be used as a tool for meaning-making in physics education. From the programming project, papers I and II, it may be concluded that programming affords some relevant possibilities to be used as a tool for meaning-making. Namely the ability to act as a transductive link between mathematical model and visualisation, the ability to offer instant feedback and the possibility to create and manipulate visualisations. These three aspects together makes programming a potent tool for learning physics.

Paper III further expands on the idea of transduction by defining the theoretical construct of a transductive link. Transductive links, and transductive chains, are concepts to help describe and identify the role of different semiotic systems within a learning situation. The concept may also be used to help plan and improve the learning sequence by identifying weak and strong pedagogical links. A strong links should help make the specific semiotic material discernible for the student as part of the transduction.

The second project aimed to investigate how social semiotics and variation theory of learning may help to guide the construction of representations for use in physics education. The project is not finished, but the data was also used for papers IV and V. Papers IV and V delves deeper into the theoretical underpinnings of social semiotics and introduces new concepts and compares the framework to the theory of registers of semiotic representations. Paper V concludes that social semiotic and the theory of registers of semiotic representations may be used together to describe learning situations in mathematics and physics education, but only if the researcher has a good grasp of both frameworks. Results from both frameworks may also be compared to each other.

Paper IV defines the concepts of active and passive transductions. The new definitions were needed because a specific learning event could not be explained using the established concepts found in social semiotics. Active and passive transductions describes the shown engagement that a student displays when performing transductions. A student may perform transductions but not engage with the semiotic material of the situation at hand.

The new constructs are also coupled to the anatomy of disciplinary discernment (Eriksson, 2019) and provides an important link between the transduction concept and disciplinary discernment.

The central construct that every paper and concept, used in this thesis, is related to is semiotic resources. Every work presented in this thesis, except paper V, may be described as understanding, modifying, or describing semiotic resources in different contexts. Papers I and II, may be described as understanding how programming may be used to construct and interpret semiotic resources related to the physics discipline. Papers III and IV both expand on the transduction concept in SS, but transduction itself involves the discernment of aspects from a semiotic resource and the construction of a new semiotic resource, or the engagement with the semiotic material that a semiotic resource makes visible. Paper VI is not complete, but is entirely focused on the creation of semiotic resources for use in physics education. Paper VII is a deep dive into what a semiotic resource is and attempts to find a new way to describe semiotic resources.

Thus, I would argue that the main subject, and conclusion, of my thesis, is that it is the manipulation of semiotic resources that provides the opportunity for discernment and meaning-making to take place. The manipulations needs to be guided and used with specific intent to help student discern, explore, and manipulate the different relevant aspects of the situation.

Implications

For researchers

By using transductive links, transductive chains, active and passive transductions, in the description of learning situations, a more nuanced understanding of the situation can be gained. The description may also be focused on how the semiotic material is modified and shifted throughout the learning situation. It is another way of describing what happens when students interact and use representations as part of their communication and meaning-making process. The aim is to identify what the transductions makes discernible an how the students discern these new aspects.

Active and passive transductions provide an important bridge between the transduction concept and the disciplinary discernment concept and may be used to design assessments or to identify student's disciplinary discernment level.

The dynamics of semiotic resources presented in paper VII also provide a new way of thinking about semiotic resources, disciplinary relevant aspects, students, disciplinary discernment, and how these interplay with each other. The toy model is far from complete, but it can be used to explore and discuss new ideas relating to modelling learning activities and student's use of representations.

For educators

If you are an educator and wants to adapt some of the ideas, or results, presented in this thesis, this is the section for you.

Using programming in physics education

First of all, if your students know programming, you may try to incorporate it in your teaching in some capacity. By using the affordances of programming to your advantage, the student may gain a better understanding of how the formulas produce the observed phenomenon, and how each element of a formula contributes to the phenomenon. Take advantage of the positive feedback loop that programming affords by creating spaces for students to explore and iterate through their ideas. Allow the students to discuss, model, and visualise the physics in their own way. Connect the student created models to the physics disciplines model, find the overlap and what they missed. This process identifies the student's relevance structure and allows you to introduce interventions where necessary.

The code used for papers I and II can be found on Zenodo (Svensson, 2020a), and may be adapted to be used in a physics classroom that teaches about forces.

Programming example: position, velocity, and acceleration

The example presented here builds upon papers I and II and attempts to capture the theoretical constructs presented in papers III and IV. The example is basic and deals with relatively simple concepts, but the same procedure may be applied to other, more advanced, concepts.

Overview The aim of this example is to showcase how programming may be used to showcase the ideas of position, velocity, acceleration, and the connection between them. By using the structure of the code and interpreting it using a physics lens, the student can explore and investigate the concepts and how they affect each other.

The Structure The exercise is structured in two parts, each with their own exploratory and interpretive phase. The first phase is the idea of capturing motion in the code. By interpreting how the code represents changes in position, the connection between position and velocity may be discerned by the student. Variations of the code will help the student discern the effects of the code and its connection to velocity. The second phase adds acceleration to the code and allows the student to discern acceleration's connection to velocity in the same manner as the connection between position and velocity.

Phase 1: velocity Start the exercise by implementing the code below[25]. The code should produce a filled disk in a window. The disk will move to the right when the program is

[25] The code is written in the Processing 3.8 IDE using the python module.

run, see Figure 32 for an example of the output from the code. The task for the students is to explain the role of the variable `change_in_x` in the code. The task for the instructor is to make the student realise that `change_in_x` is connected to velocity. This should be done using variations of the variable's value. By changing the value of `change_in_x`, its effects on the moving disk may be discerned. `change_in_x` should be identified as the velocity multiplied with time. Use dimensional analysis to showcase that velocity needs to be multiplied with time to obtain a position.

```python
# position of disk
x = 100
y = 200

# initiate a window
def setup():
    size(500, 500)

# called every frame
def draw():
    global x, y

    # draws a circle at position [x, y]
    circle(x, y, 50)

    # change x-value each frame
    change_in_x = 1.5
    x = x + change_in_x
```

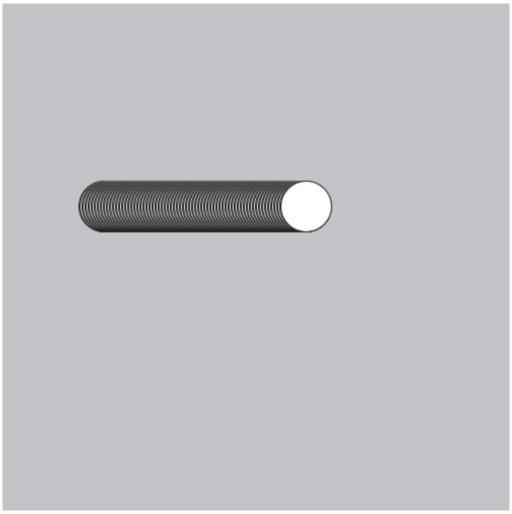


Figure 32: A filled disk is drawn at new locations each frame, indicating that it is moving.

After students have identified change_in_x as velocity multiplied with time, it can be changed in the code:

```
    # change x-value each frame based on velocity and the timestep
    velocity_x = 1.5
    timestep = 1.0
    x = x + velocity_x * timestep
```

The same procedure can now be done for the y-direction to showcase that the disk has several degrees of freedom. It can move in the x-direction and the y-direction. Make the student vary the velocity in x and y directions separately to obtain different speeds and directions for the velocity of the disk. The aim is to connect what the student observes in the visualisation to the values they change in the velocity variables. It also helps to name the initial variables in ways to describe what their role is in the program, such as change_in_x and after observing its effects, connect it to a physical idea, such as velocity.

Phase 2: acceleration By expanding the program with the code below, a new effect may be observed in the simulation: the disk falls down and to the right. This can be seen in Figure 33. The same approach as for velocity should be employed to identify change_in_velocity_x or change_in_velocity_y with the change in the visualisation and connect this to the concept of acceleration.

```
# position of disk
x = 100
y = 200

# velocity of disk
vel_x = 1.5
vel_y = 0.0

timestep = 1.0

# initiate a window
def setup():
    size(500, 500)

# called every frame
def draw():
    global x, y, vel_x, vel_y

    # draws a circle at position [x, y]
    circle(x, y, 50)

    change_in_velocity_x = 0.0
    change_in_velocity_y = 0.05

    vel_x = vel_x + change_in_velocity_x
```

```
    vel_y = vel_y + change_in_velocity_y

    x = x + vel_x * timestep
    y = y + vel_y * timestep
```

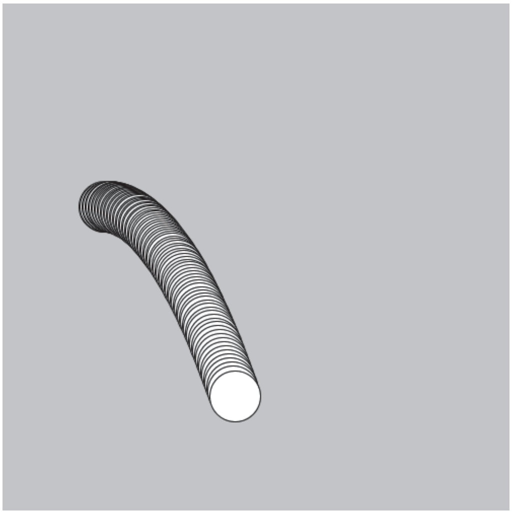


Figure 33: A filled disk is drawn at new locations each frame, indicating that it is moving. The velocity is changed in the y-direction, providing an acceleration downwards for the disk.

Applying the theoretical constructs In the programming example above, variation of variables and recognising that the change in the visualisation is a direct result of the change in the code employs ideas found in variation theory of learning. The changing of variables and writing, and rewriting, of code employs the idea of translation from social semiotics. The movement between code and visualisation draws upon the idea of transductions from social semiotics. By asking the student to identify and describe what they see in the visualisation and how it relates to the code encourages the student to perform active transductions. The active transductions provide insight into the student's understanding of the situation using the anatomy of disciplinary discernment. The different phases construct a useful flow of semiotic material by relating position to velocity in phase 1, and velocity to acceleration in phase 2. Velocity is used as the transition between the phases, ensuring that the semiotic material is conserved.

After the exercise After the students have gone through the programming they should be introduced to the mathematical representation of position, velocity, and acceleration. The introduction of the mathematical representation should aim to connect them to what was coded. This is to ensure that the student realises that a concept can be represented in different ways and depending on the situation, different representations may be more useful than others.

Adapting the theoretical constructs

If you wish to employ the theoretical constructs of transductive links and active and passive transductions in your teaching, I would recommend that you employ them as you plan your teaching, or when you want to renew your teaching. By thinking of your lectures as chains of transductions, you may identify weak links, or points where the semiotic material is hard to follow from one semiotic system to another. It allows you to examine, and plan your own teaching with new eyes.

When doing learning activities that involves the student's movement between different semiotic systems, try to encourage active transductions. That is, make the student unpack the semiotic material, have them explain the different parts, make them identify aspects that connect one representation to another. This will result in the transduction being an active one and the student will unpack, highlight, and filter, aspects as they perform the transduction. However, if there are to many active transductions, that is; the student has to show engagement with every aspect of the situation, they may experience cognitive overload. Try to identify some transductions that would provide you with useful information if the student were to perform them as active transductions and leave the rest of the transductions as passive transductions.

Contributions to PER

Overview

The largest contribution to the PER-community is my work around semiotic resources and how semiotic resources are tied to disciplinary discernment, transductions, affordances, and the flow of semiotic material. Below is a list of specific contributions to the physics education research community based on the papers presented in this thesis.

Research contributions to programming in physics education research

The following contributions may be found in papers I and II.

- A theoretical analysis of programming using social semiotics and variation theory of learning.
- The identification of programming as a potent tool for learning physics, using the lens of SS and VTL.
- The identification of the affordances of programming for physics education.

Research contributions to comparing theoretical frameworks in physics education research

The following contributions may be found in paper V.

- The identification of the similarities between social semiotics and the theory of registers of semiotic representations.
- The idea that both frameworks may be used together, if the user has knowledge of both frameworks. Results obtained using social semiotics can be compared to results obtained using the theory of registers of semiotic representations.
- Shown the advantages of performing a comparison between theoretical frameworks: the potential for further development of each framework.

Research contributions to theoretical development in physics education research

The following contributions may be found in papers III, IV, and VII.

- Provided a definition for Transductive links so that the concept may be used in PER.
- Expanded upon transductive links into Transductive Chains and connected the concepts to the multifaceted way of knowing.
- Identified and defined active and passive transductions and their implications for assessment.
- Connected active and passive transductions to the Anatomy of Disciplinary Discernment.
- The introduction of a mathematical model to discuss and explore ideas in PER.
- With the mathematical model: A better understanding of the relationship between semiotic resources, disciplinary discernment, and affordances.

Further research

Based on the research presented in this thesis, the following venues of research are proposed.

- Investigate teachers thoughts about using programming in physics education, in the same manner as programming was used in papers I and II. Explore how the affordances of programming could be employed to introduce programming to physics education.

- Explore what type of physics may be possible to teach if the student-body is literate in programming.
- Explore and identify different transductive links with the intent to classify different links into groups with similar affordances.
- Further develop Social Semiotics by further developing the mathematical model of paper VII.
- Introduce directionality of transductions, a concept that already exists for conversions in the theory of registers of semiotic representations.
- The connection between social semiotics, cognitive theories and learning activities in physics education.

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Scientific publications

Author contributions

Paper I

I came up with the initial idea and performed the data collection and analysis. UE, AMP, and LO provided useful comments and inputs at each stage of the study and helped guide the paper.

Paper II

I and UE together identified the possibility of describing the affordances of programming using SS and VTL. UE and AMP advised in the analysis and in the writing of the paper.

Paper III

I, together with UE, identified transductive links as a useful construct. I wrote the paper and UE supported the process through discussions and comments.

Paper IV

I and EC identified a gap in the transduction-concept. I, UE, and JL, defined and explored the concept, with input from EC. I wrote the paper with input from the other authors.

Paper V

I initiated the idea and collaboration. I also performed the data collection, with input and guidance from EC. EC and I both analysed and wrote the paper.

Paper VI

I came with the original idea. UE and JL supported and guided the data collection. Analysis is still on going.

Paper VII

I came up with the idea and wrote the paper. UE and CL guided the development of the idea through discussions and comments. UE, CL, and JC, provided extensive comments on the paper.

Published papers and drafts

The following papers are reprinted in this thesis.

Svensson, K., Eriksson, U., Pendrill, A.-M., and Ouattara, L. (2020). Programming as a semiotic system to support physics students' construction of meaning: A pilot study. *Journal of Physics: Conference Series*, 1512(1):1–12.
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Svensson, K., Campos. E. (202X) How do students use representations in physics? A comparison of two semiotic perspectives
Submitted to *Physical Review Physics Education Research*

Svensson, K. (202X) Constructing representations based on Social Semiotics and Variation Theory
Draft, not yet submitted.

Svensson, K., Eriksson, U., Linder C., and Clark, J. (202X) Dynamics of semiotic resources
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Paper I

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Programming as a semiotic system to support physics students' construction of meaning: A pilot study

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Abstract. Programming as a tool to be used for analyzing and exploring physics in an educational setting offers an unprecedented opportunity for the students to create and explore their own semiotic resources. Students may use programming to create and explore different models of physical systems. In this study a small group of upper secondary education students participated in a workshop where they learned to program physics simulations and to create their own models to implement using the programming language Python. Results from the study shows that upper secondary education students are able to create their own models of physical systems and implement them into code. The implemented models were models of hanging cloth and heat diffusion. Results were obtained by analyzing video and audio recordings of the students through the lens of social semiotics.

1. Introduction

In Sweden, a push to use programming outside of the programming class has been ongoing for years. From the summer of 2017 it is mandatory to have programming elements in mathematics from year one of elementary school [1]. It does not start with coding, but with algorithmic thinking and figuring out rules and models for solving problems and then transitions into implementation and validation. Digital resources and digital competency comprises a large part of the evolving educational system in Sweden. The focus is on dynamic representations, such as animations, simulations and interactive elements where the user can interact with the representation to observe changes and variations of different aspects [2].

Physics and mathematics are closely related to each other ever since Isaac Newton's formalisation of motion, giving natural philosophers another way to investigate natural phenomena. Programming has been used in physics and physics education for a long time, but it has rarely been used explicitly to give students a new tool that they can use outside of class [3, 4, 5]. We propose a more exploratory use of programming, where students define their own models and implementations, allowing them the freedom of variation [6], both in implementation and visualisation. This approach is believed to provide the student with meaning-making opportunities through the process of creating/implementing/testing their models.

In this paper we study a small group of six 17-18 years old students, with mixed genders, in upper secondary school with an interest in physics, to see how they approach physics problems and concepts within a programming setting. The students volunteered to be part of the study after learning about it during a physics-based event at Lund University. All students came from the same school and the same class, they were friends and had no problem discussing or speaking to each other. Special focus was given to analysing their understanding of the use of programming as a tool in physics. These students were chosen because of their interest in physics and their experience/lack of experience with programming. The aim of the exercise was to make the use of programming more explicit and to give the students a new tool to use for creating and investigating models of physical phenomena. One of the overarching aim of this study is to see what level of programming proficiency is needed to use programming in this manner. Half of the students had had some form of programming experience, equivalent to a basic course in programming, before participating in the workshop.

It is through the lens of *Social Semiotics* [7] that the different aspects of programming can be analysed and given a meaning potential. This work is both theoretical and empirical in the sense that, through Social Semiotics, the strengths of programming as a tool for meaning-making can be identified and then used as a lens to study how students use, or interact with, programming in a physics environment.

2. Theory

The Social Semiotics framework is the lens used to study and explain the students' reactions and actions in this pilot study. Social Semiotics was started by Michael Halliday [7] and looked at language as the main communication method. It has since grown to encapsulate many different forms of communication methods and systems [8, 9, 10]. John Airey & Cedric Linder [8] defines social semiotics as: *the study of the development and reproduction of specialised systems of meaning making in particular sections of society.* This is also the definition used in the work presented in this paper.

2.1. *Social Semiotics and Programming*

Programming fits very well in the social semiotics framework thanks to its ability to reproduce and develop specialised systems. The production of specialised systems, through programming, can be seen as meaning-making functions. By creating and implementing models of physical phenomena, insights into the structure of the model, its dynamics, can be obtained. We believe that programming may help the student gain specific insight into the physical phenomena that is being simulated.

In programming, there is no need for explicit communication of the students' idea to other students/teachers, but only to the computer. The interaction between student and computer becomes the disciplinary communication and meaning-making activity used to create/extract meaning. The interplay between student and computer allows the student to ask their program questions and analyse the answer, such as: "What if Hooke's law is $F = kx^2$ instead of $F = -kx$?" These kind of questions and the ability for the student to, quickly and easily, observe the results allows the student to explore and experience variation of key aspects of the students own mental-model of the physical model.

A teacher or TA should help students realise the potential of asking the program questions and analysing the results. The teacher or TA should also help the students exploration through guided questions or "what if" scenarios.

2.2. *Semiotic Resource*

A semiotic resource is defined by Linder et al. as: "Anything that is used to make meaning in a disciplinary relevant manner" [8]. Which includes representations, tools and activities. Within the physics discipline we have many disciplinary-specific semiotic resources such as: particle detectors, right-hand rule, Feynman diagrams and many more. Each semiotic resource have some specific disciplinary meaning for the discipline. A student must learn to use, create, read, and analyse these resources if they are to become part of the physics discipline.

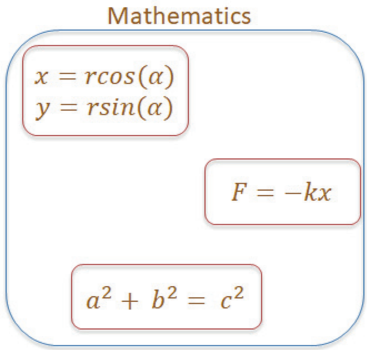

Figure 1. Different semiotic resources (red) relation to their semiotic system (blue). Each of the resources are different and are used in different ways in different scenarios, but they all belong to the same semiotic system.

2.3. Semiotic System

A semiotic system is defined by Linder et al. as:"Qualitatively different ways of communicating disciplinary relevant knowledge" [8]. See Fig 1 for a visual interpretation of the relation between semiotic systems and semiotic resources. Only when a semiotic system is used in a specialised case is a semiotic resource created/retrieved, as can be seen in Fig 1. A student must be able to extract relevant semiotic resources from different semiotic systems to solve different physics problems or to set up their own models and theories [11].

2.4. Transduction and Transductive Links

Within the physics discipline it is required to move between different semiotic resources and between semiotic systems, such as: going between a function and its graphical representation. The transformation between semiotic systems is called a *transduction*. Transductions are everywhere in communication: going from speech to gesture to drawing to speech and so forth. Each of these transductions is designed to move the focus from one semiotic resource to another with the purpose of highlighting some important aspect. Some semiotic systems aid the transduction from one semiotic system to another, these are called transductive links. Gestures are often used as transductive links between semiotic systems that are easier to extract disciplinary meaning from. Gestures allows the user to move quickly between different semiotic systems without losing focus of relevant aspects.

2.4.1. Programming as a Transductive Link Programming can be viewed as a transductive link between many different semiotic systems since it may take many different inputs and produce many different outputs. Due to the versatility of programming it can be described as a universal transductive link since it may move between many different semiotic systems.

The student constructing a program is responsible for the transduction taking place and is explicitly expressing the rules for the transduction. This provides the student control over the transduction, it allows the student to choose how to do the transduction and how to represent the new semiotic resource.

Figure 2. Programming is a universal transductive link since it can act as a stepping stone between many different semiotic systems. The student has full control over the transduction step and can choose the final products semiotic system at will.

2.5. *Affordances and programming*

An object or resource can have different affordances. An affordance is something a resource offers to an agent. Different resources offer different things and thus have different affordances. For example, a bottle of water affords ’Drinking’ and ’Holding’ and many other affordances. Within the social semiotic framework, two useful affordances have emerged:

Pedagogical Affordance: *”the aptness of a semiotic resource for the teaching and learning of some particular educational content”.*

Disciplinary Affordance: *”the agreed meaning making functions that a semiotic resource fulfils for a particular disciplinary community”.*

as defined by John Airey [12]. These affordances offer a way to study semiotic resources and say something qualitative about them. One of the goals of teaching would be to use resources with high pedagogical affordance and slowly transition into using resources with high disciplinary affordance. Tobias Fredlund [13] showed that different semiotic resources within the same semiotic system can have very different levels of pedagogical and disciplinary affordances.

Programming, through its power as a transductive link, allows the student to create their own semiotic resources. These new resources have their own disciplinary and pedagogical affordances which are directly, albeit unknowingly, controlled by the student. The student can thus create resources that have a balance of affordances that matches the students own ability to extract disciplinary meaning from it. Some students may spend extra time to create a resource with higher pedagogical affordance, to facilitate meaning-making, see Figure 3. Other students may extract meaning from highly abstract visualisations and instead increase the disciplinary affordance of the resource.

2.6. *Coding, Visualisation and Interaction*

The National Agency for Education in Sweden uses a broad definition of programming which includes: algorithmic thinking, creating dynamic representations (visualisations), producing coherent models and implementing them in code [2]. This view of programming is also the view taken in this research. We have decided to combine all of the different programming parts into the following aspects: coding, visualisation and interaction. Special focus is placed on the interplay between the three aspects and how they allow the student to open up dimensions of variation[6] of different disciplinary relevant aspects[13]. This approach is a step up from Orban et al. [14], where they specifically looked at coding and interaction. Together, coding,

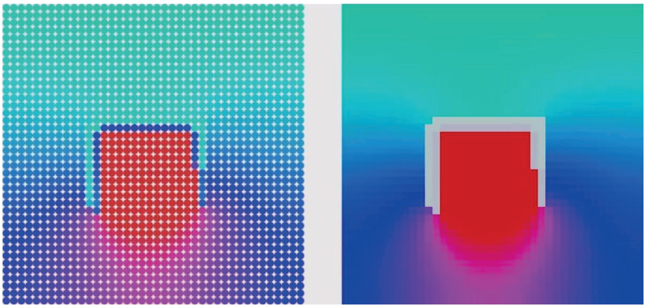

Figure 3. A standard visualisation is shown on the left. On the right is a visualisation created by a student who altered the original visualisation. The semiotic resource on the right has higher pedagogical affordance since it allows for easier extraction of relevant disciplinary information whereas the information in both resources are the same.

visualisation and interaction allow the student to code their own model, visualise it and interact with it to explore different scenarios.

Dimensions of Variation is a term from the Variation Theory of Learning [6], where learning occurs when the learner discerns variation in the object of learning. By varying the aspect the object of learning with respect to a static background, that aspect is highlighted and discerned, learning takes place. This is the main tenet behind using coding, visualisation and interaction as a package since it provides the student with the ability to vary all aspects of the simulation and its representation. It is hoped that the student realises the potential of programming and varies whatever aspect they are interested in to gain new insights into the physical phenomena they are exploring.

3. Research Questions

This research is designed to answer the questions below, but also to see if there are any programming related learning scenarios occurring during the workshop. An example of such a scenario can be seen in section 5.3 where students investigate predictions of their models using the real world, but also using an interactive simulation.

- How can Social Semiotics be used to describe learning physics using programming as a semiotic system, based on the reported experiences by the students?
- What does the participant students report about using programming to explore and learn physics?

4. Methodology

A workshop was created with the purpose of unlocking the potential of programming as a tool to understand physical phenomena for the students. To do this, the workshop relied heavily on variation theory to highlight different aspects of programming. The students were encouraged to vary different aspects of the code such as: the interaction between particles, the visualisation and the interaction with the simulation. Through these variations the student could highlight different aspects that caught their interest. The workshop was especially designed to be versatile with respect to the different kinds of physical phenomena that can be simulated. The different sections of the workshop and their purpose for unlocking the potential of programming can be seen below. Each session was two hours long and was video and audio recorded from several angles. During the sessions, smaller interviews were done to capture the students thinking about kinematics and attempts were made to observe changes to their thinking through video recordings. Each session was self-contained and the content did not bleed over into the other session.

Each session was set out as a Code-Along, where the students coded along with the lecturer. At each step of the implementation, the students were encouraged to test and vary things in the code to understand how it behaved. The programming language used was Python using the Processing IDE, which allows for easy visualisation, interaction and quick iterative coding.

The sessions took place over six weeks in May and June in 2018. The first four sessions took place during the four first week of the interval and the last session, the interview session, took place during two weeks after. The gap was due to a national holiday happening on the same day and it was not expected that the participants would participate on that day. Each session took place on Saturdays before noon.

- Session 1 was designed to make the students familiar with the programming environment and introduce key aspects of the engine such as the updating loop and the ability to draw shapes in a window. The students coded along with the lecturer and constructed a circle that had its position updated between each frame, creating an animation of a ball moving. The ball was given velocity and acceleration which in turn allowed the ball to showcase ballistic motion in the window.

- Session 2 focused on taking what was created in session 1 and combining it all into a Particle-class. The Particle-class can update its position using an Euler-Cromer [15] integrator, it can show itself in the window and it can feel forces. During each timestep, the particle calculates new accelerations from the forces it feels, it then uses the acceleration to update its velocity and position. The students coded along with the lecturer and was encouraged to vary different attributes of the particles to see that particles with different values can be created but they all follow the same code. In session 2, the notion of interaction between different particles was introduced and the interaction was limited to forces.

- Session 3 was divided into two parts. First, the students were divided into groups of three and each group was tasked with coming up a model to simulate hanging cloth. The groups had thirty minutes to come up with a model and they had access to a interactive simulation of hanging cloth but they had not access to the code for the simulation. The group then presented their models and discussed. In the second part of the session, a hanging cloth simulation was created by the lecturer with the students coding along. The dire

- Session 4 instructed the students to come up with, and implement, their own models for heat diffusion and then compare their models with the textbook formula for heat diffusion. The lecturer helped with programming questions and advice regarding potential pitfalls. The of this approach was to create an environment where data, about the students ability to formulate their own models and testing them, could be obtained. The students had to figure out how to represent thermal energy and heat between different particles, how to update the attributes and how to visualise it. See Fig. 3.

- Session 5 was an interview session consisting of individual interviews as well as a group interview. Questions were designed to highlight their vision of programming as a tool to investigate physics, what they can use it for and what they want to use it for in the future.

In essence: The workshop was designed to create a solver for ordinary second-order differential equations such as the kinematic equations from Newtons laws of motion. The setup of the solver allows the student to easily access different parts of the interaction and change them to create new models and simulations. The easy interpretation of the implementation of the solver is created to place the attention of the student on other aspects of the program.

4.1. Analysis

To analyse the video interviews and workshop sessions a qualitative analysis method is used. By transcribing the videos, with a special focus on disciplinary relevant events, categories about the students conceptual understanding and its relationship to programming can be inferred. The student's relationship to programming and their ideas about future use of programming can be seen from the categories.

The categories have yet to be finalised but will follow from the theory of Phenomenography [16], where a phenomenon is experienced by agents and their experience about the phenomenon is categorised into qualitatively different chunks.

5. Results

All students managed to follow along during the sessions regardless of their programming experience prior to taking part in the workshop. Three of the six students had some prior knowledge of programming and three of the students had close to no experience of programming. When asked about what programming offers or differs from a normal physics education situation two of them said:

Student 1	[Programming] has given me, that I can take a phenomenon or problem or . . . **anything** . . . from physics. Implement it and visualise it and . . . **figure out answers** and **see if I've done it correctly.**
Student 2	. . . something else I thought about. . . **that programming gives another angle on the physics**. Often, you have exercises you have to solve, and that is the case in programming as well, if we would simulate a pendulum, but its much more. . . vague. There are different ways to do it. **Instead of just solving something, you create.**

These answers shows that the students have seen the potential and the use of programming in physics and how they may apply programming to investigate physics. The second student also separated programming from normal exercises within physics education in the sense that in programming you do not solve a particular problem, but you create a whole system capable of solving many exercises.

5.1. Programming Proficiency

All students managed to follow along in all the sessions. The students with prior programming knowledge began using programming at home or in school for smaller projects. The students all agreed that an introductory course in basic programming would be good, and they also said that they do not think anything more were needed to use programming in the way they had in the sessions.

5.2. Dimensions of Variation

One student created a small simulation of a Frisbee and said that the direction of forces had become much more important than before. The student had had to think much more carefully about the directions of forces than they had before this small project. A new dimension of variation had opened up when implementing the model for the Frisbee, namely that the direction of forces can change.

Another student did some programming ahead of time, because they realised where the session was headed and realised that they could implement it themselves. At the end of the session it turned out that they had written a correct solution, but used a different approach than what was shown by the lecturer. The student then asked if it was acceptable to write different solutions. [The answer is, of course,Yes!]. This opened up a dimension of variation for this student: the ability to vary the solution, or to vary the approach or implementation of the idea.

A third student varied the visualisation during the last session to make it more visually appealing, see Fig 3. This opened up yet another dimension of variation: namely the ability to represent data in different ways to highlight different aspects. During the second session, the colour of particles where coupled to different aspects such as its position, velocity and acceleration, this coupling of the visual to variables gave the student a way to showcase different aspects that they were focused on.

5.3. Making and testing predictions

During the third session, the students were tasked with constructing a model for hanging cloth. During this task, they had access to an interactive simulation of a hanging cloth to act as inspiration.

The interactive simulation took on an unexpected role of being the validation medium for their models. Before the students' models were implemented, the students made predictions about the behaviour of their model and came up with scenarios to test using the interactive simulation.

Student 4	”Can you throw the curtain above...?”
Student 1	”Yes, but it can go down. Then **it [their model] does not work** if we can pull it down.”

The student used the interactive nature of the simulation to test their prediction and to find new aspects that they had not thought about. These interactions made them rethink or adapt their own model to fit with the interactive simulations behaviour.

Another example of implementing models and making predictions come from the fourth session as Student 5 manages to get their simulation to work:

Student 5	”YES! **It does what I want!**” [Student 5 puts their hands up the air, they also stand up and clap their hands]

Apart from being a celebratory occasion, this also showcases that Student 5 had expectations of their model. They understood what they wanted from the model and could visualise the behaviour of the model in their head. When the implemented model was visualised Student 5 could immediately identify that they had implemented it correctly. Student 5 thus used the visu- alisation of the simulation to validate the behaviour of the simulation versus how they expected in to work.

5.4. Getting the full picture

Student 4 realised that the dynamics of the cloth simulation would drop out as long as the base interaction between particles were implemented correctly. As one group of students were discussing their model, the problem with interactivity (dragging the mouse across the hanging cloth) came up:

Student 1	”Shall we start wondering about what happens when we throw in a ball?” [Student 1 picks up an eraser and moves it towards the drawing on the whiteboard.]
Student 4	”...actually, I think if we just have a**good simulation at the start...**”

Student 4 implies that the simulation will handle the interaction with the ball without problems if the base of the simulation is good. This insight is true and goes even deeper, student 4 realised that the phenomenons they had observed in the interactive simulation or the phenomenons they expected to observe was the result of the basic interactions between individual particles.

Another student, Student 3, also realised that the model used to implement the physics can be represented in different ways. Student 3 realised that the particles used in the simulation are just the ”physical background” which handles the simulation and that they can be represented in various ways on the screen depending on what they wish to highlight.

Student 5	”It is the particle inside that is good to have for the distance...” [Student 5 gesticulates and pulls out a thread (in the air).]
Student 3	”No, we have to have something, the particles are only there for the thing, then we we may place squares over them to make it look nice. **These round things are only there for the physical background.**

6. Discussion

Social Semiotics, and its semiotic resources and semiotic systems, provides well adapted tools to investigate programming as a tool for learning within physics education. By identifying the interaction between student and computer as communication, the tools of social semiotics can be applied such as variation theory and transduction. Programming is especially well suited to exploit variation theory due to its well defined structure, by changing single variables or small bits of code and observing the effects of this variation, concepts or connections can be discerned which would be hard to discern from just a formula. Programming also allows student to make well defined transductions between different semiotic systems. The transductions require the student to unpack the semiotic resource they are moving from one semiotic system to another. The unpacking of semiotic resource reveals the inner structure of the semiotic resource that is being transduced, allowing for discernment of its various important parts.

Within this study, it has been shown that students with interest can use programming to create, implement and visualise their own models of physical phenomena. However, they all agree that a basic knowledge of programming would help them to easier implement their own ideas or models. The students also said that implementing physical models into code highlighted different aspects,that they had not focused on when solving normal physics exercises, such as the direction of forces when implementing a model of a Frisbee. Programming also allowed them to rapidly change their models based on the visual feedback from the simulation. This created a feedback-loop where the students could iterate and test different aspects of their model using variation of different aspects.

7. Conclusions

Students with an interest in physics and programming were able to see the potential of programming as tool to be used when learning/investigating physics and physical phenomena. Some programming knowledge were needed to apply the programming to their own ideas, but only the basics of programming knowledge such as: If-statements, For-loops, Variables, Lists/Arrays. Knowledge of classes help, but is not needed to produce the simulations.

Programming allows the student to open up many different Dimensions of Variation to explore. Since the student is the programmer, they choose the dimensions of variation themselves and thus focus on the aspect they wish to understand.

Students can use the interactive nature of the simulations to test predictions and to construct new scenarios were they cannot predict the results.

Programming fits well into the Social Semiotics framework and programming is a powerful tool when looked at as a transductive link between semiotic systems where students are allowed to create their own representations through transduction from one semiotic system to another.

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Paper II

Programming and its affordances for physics education: A social semiotic and variation theory approach to learning physics

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A small group of interested upper secondary education students participated in a workshop where they created a particle-based physics engine and used the engine to implement a hanging cloth simulation and a two-dimensional heat diffusion model of their own creation. During the implementation of their models, learning opportunities present themselves in the form of opening up and exploring different dimensions of variation for the students. By varying aspects and discerning how these changes affect the program, students can construct meaning about the system. The students were video and audio recorded during the workshop and interviewed afterwards. Based on the transcripts, students use of programming was analyzed using social semiotics and variation theory of learning with a focus on the three aspects: coding, visualization, and interaction. The analysis identifies usages of programming such as a transductive link between semiotic systems, the ease of varying and iterating aspects, and the ability to enter into a loop of discovery and understanding.

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I. INTRODUCTION

This paper aims to highlight why programming could be a useful tool for meaning making in physics education and focuses on the interplay between coding, visualization, and interaction. By describing programming as a semiotic system (described below) to be used in communication and meaning making in physics education, a theoretical framework is provided that allows us to study programming through the lens of variation theory by focusing on how programming's affordances change (also described below). A small group of upper secondary education students, who knew each other well, participated in a study designed to take them through the process of creating a physics simulation using Python [1] in the Processing IDE [2]. Our study investigates to what extent the students were capable of using programming to extract meaning from simulations, how they modified the resulting representation and how they interacted with the simulation.

By using logical operators and algorithmic thinking, programs can be constructed that perform a wide range of different tasks, such as simulating different physical phenomena. In physics, a student may create a model of a physical concept, run the simulation, and ask "What happens in this specific scenario?" The student may then analyze the output from the program to get an answer to the question. Whatever answer produced by the simulation, the student has an opportunity to learn something; if the answer is an "error" the student has been informed where their code may be wrong and can change the code and in the process they explore and learn different aspects of the concept they are implementing. If the simulation conforms to the expected behavior, questions about the content of the simulation can be asked. There is a "communication" between the program and the student, where the student tries to extract relevant information, through the visualization, from the program about different aspects of the model they implemented.

In a simple simulation, where a planet orbits a star, the student may ask "What happens if I change the mass of the planet?" If the student has implemented a correct version of Newton's law of gravitation, $F = GmM/r^2$, there should be no change in the behavior. However, if there is an error in the implementation, the planet will behave differently and the result will differ compared to real world experiments and expectations. The student may then create a plethora of different simulations to observe if any conforms to experiments done in the real world. Programming allows for an iterative and exploration-based approach to learning physics and making models.

The paper begins with an overview of the theoretical framework used to analyze programming in physics education. A small study, with the aim to investigate the claims

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of the theoretical framework, and its results are presented. The discussion focuses on explaining the results using the theoretical framework and concludes that the framework offers a new and innovative way of describing the learning experience provided by programming in physics education.

II. BACKGROUND

Programming is an important aspect of current physics research and is not new to physics education. In the 1980s it was used by Seymour Papert [3] with the Mindstorms system, which was later adopted by LEGO in their Mindstorms [4] production line. Programming was also used with the MUPPET program [5,6] in physics education as a way to explore different concepts found within the physics discipline. With the introduction of higher level programming languages, more research into the use of programming in physics education has been performed, for example, Refs. [7–10], which focused on fostering computational thinking. Using programming, many different animations and simulations have been created and their usefulness for conceptual change and physics education have been investigated [11–13]; with the findings that animations and simulations help students understand concepts better. This is true not only in physics education, but in other science education settings as well [13–16]. Kuo-en Chang *et al.* [11] found that allowing the students to formulate their own hypothesis about a physical concept and then test the hypothesis allowed for more conceptual change than a step-by-step instruction when using a simulation.

Several programs have been created with the sole purpose of being used in education, in various disciplines, such as MuPPET and NETLogo [5,17], and the American Association of Physics Teachers [18] argues that programming and the knowledge of creating and using simulations to investigate and explore models of physical phenomena, should be a crucial part of modern physics education. However, programming and simulations must be implemented into the courses and into the curricula into a meaningful and useful manner [19–22]. The focus of the implementations, performed or analyzed in Refs. [19–22], have been to foster computational thinking in the student, where programming can play an important role, but is not required. Programming has been recognized to have the potential as a great tool for physics education [6]. However, the implementation, usage, and goals when using programming differ from location to location and from teacher to teacher.

The theoretical aim of this paper is to look at programming as a phenomenon and its specific usefulness in physics education through the lens of *social semiotics* (see below). It is the combination of coding, visualization, and interactive activities that gives programming the versatility to be used in many different fields of physics research such as cosmology, fluid dynamics, and atomic physics. By studying not only the code, but the visualization and how to interact with the program, it is believed that a much richer understanding of the potential use of programming can be gained. This larger view of programming is also the view taken by The Swedish National Agency for Education (Skolverket, Sec. 1.3 [23]).

III. THEORETICAL FRAMEWORK

Below is a description of the theoretical frameworks used in the analysis of programming. The analysis combines social semiotics (Sec. III A) and the variation theory of learning (Sec. III C) and finds their ideas useful for describing programming as a means for meaning making in the physics classroom.

A. Social semiotics and programming

Social semiotics [24–27] is a theoretical framework built around understanding and investigating group meaning making and the resources that are used to create meaning through communication. The resources are called *semiotic resources* and encompass "representations, tools, and activities used to create or derive meaning in specialized groups" [25]. Using this definition, we may look at programming as a means for communication between student and program. A student may ask questions of a program to get an answer, or as a means to construct new representations or tools. However, programming is not a semiotic resource; instead it should be seen as a *semiotic system* [28] because programming can be used to describe many different scenarios and be used to extract many different answers to many different questions. A specific semiotic resource is used in a specific scenario to convey a specific meaning, such as a time-velocity graph or a specific circuit diagram. A semiotic system is a system of communication that is qualitatively different from other means of communication. The communication system "image" is a semiotic system that is qualitatively different from "text" which is another semiotic system. However, text can be used to convey different meanings in different situations: When a semiotic system is applied in a specific scenario, a semiotic resource is created or extracted from it. An author uses text to write a book, the book is the semiotic resource and the text is the semiotic system used to produce the semiotic resource. Many different semiotic systems may be used in tandem to create a single semiotic resource such as this paper which uses the semiotic systems text and image to convey meaning in a disciplinary relevant manner.

Programming can be described as a semiotic system used to create or investigate other semiotic resources. By using programming it is possible to move between different semiotic resources and between different semiotic systems, such as taking a long list of data points as the input and produce an animation as the output. The programmer has transformed a semiotic resource (a specific list of data points) in a semiotic system (list of numbers or data) to another semiotic resource (a specific animation) in another semiotic system (animations). This kind of transformation is called *transduction* within the *multimodality* framework [29], or a "re-representation." Transductions are important in physics education [30–32] because they force students to discern the relevant aspects represented in different ways. Transductions can be complicated or hard to grasp and students should be given the time to explore and understand them [33]. Programming is well suited for student-controlled transductions because they perform the transduction at every step of the implementation, from the initial mathematical model to the visualization on the screen. The importance of using multiple representations for enhancing learning has been explored by, e.g., Refs. [34,35], who found that when and how students use multiple representations plays an important role in student learning. Often, but not always, the use of multiple representations has been found to be beneficial for student learning. This is also confirmed by the social semiotic framework, where Refs. [25,28] model this in terms of "critical constellations" of semiotic resources.

B. Affordances and programming

Affordances is a term used to describe what different objects offer a student that interacts with the object [36]. If a student interacts with a bottle, they may get the urge to "drink" or to "pour" or, if the bottle is empty, to "throw away" or "recycle" or to "fill" the bottle. These are all examples of affordances of the bottle. However, if another student interacts with the bottle, they may extract other meaning or urges from the bottle. What the bottle affords the second student differs when compared to what it affords the first student. This difference can be explained by how the two students discern different affordances. Which affordances they will discern depend on their prior knowledge, profession and many other factors such as their mood and the setting they are in. The bottle has a multitude of different affordances, but which affordances are discerned depends on the student interacting with it. For example, a professor in particle physics will discern some disciplinary relevant meaning from the formula

$$A_{\mathrm{PV}} = -m_e E \frac{G_F}{\sqrt{2}\pi\alpha} \frac{16\sin^2\Theta_{\mathrm{cm}}}{(3+\cos^2\Theta_{\mathrm{cm}})^2}\left(\frac{1}{4} - \sin^2\theta_{\mathrm{W}}\right).$$

The professor's discerned meaning probably differs from what a novice in the physics field may discern from the same formula.[1]

Programming offers the student the opportunity to modify the code with the intent to increase the discernibility of different aspects. What a student discerns is based on their ability to extract meaningful information from the resulting representation; by modifying the representation, students may discern relevant aspects more easily. Programming also requires that each part of the implementation is made explicit, and therefore requires discernment of its different parts, and opens up the possibility for learning [38]. The theory of affordances has been put to use in physics education by Refs. [25,39,40] and has morphed into disciplinary [41] and pedagogical affordances [42] which describe how well a semiotic resource can be used, or is used, in the discipline or as a pedagogical resource.

This paper does not use the term affordance that Norman [43] introduced, which states that affordances are only related to the physical interaction between the actor and the object. This paper uses the term affordance as describing anything that an object allows an agent to discern from it. Thus, it is possible to add and remove affordances as well as change the existing affordances by modifying an object. This use of affordances is much closer to how the social semiotics and the multimodality [29,44] communities use the term and can be read as the "meaning potential" of an object.

1. Semiotic resources and affordances

Semiotic resources used in teaching and learning offer certain meaning for the student to discern, or intended meaning. We may look at what a semiotic resource offers and what a student can discern from that semiotic resource to ascertain how well they understand a specific concept [40]. If a semiotic resource does not offer a specific meaning-making affordance, no student may discern that meaning from it. However, if the semiotic resource was modified, it could gain the specific affordance needed to convey the intended meaning and be used in communicating and understanding the intended meaning. A modification of a semiotic resource could be as simple as a person saying "This pen is a spaceship," which allows a student to discern spaceship-relevant aspects from the pen. A change in the semiotic resource is accompanied by a change in its affordances. See Fig. 1 for a visual demonstration of how a change in the semiotic resource also changes how well specific meaning can be extracted from the semiotic resource. In Fig. 1, no new information was added in the transformation, only how the information was represented. The affordances are separate but related to the information and meaning contained within a semiotic resource. However, changing the affordances of a semiotic resource is no precise art and is mostly guided by conjecture and educated guesses.

2. Modifying the semiotic resources

Whenever a semiotic resource is modified, by adding color, gestures, description, or any other modification, the affordances of the semiotic resource are modified or adjusted. The change may increase, decrease, or remove the discernibility of an affordance. Programming allows the

[1] The formula describes the probability of two electrons scattering off each other through Möller scattering [37].

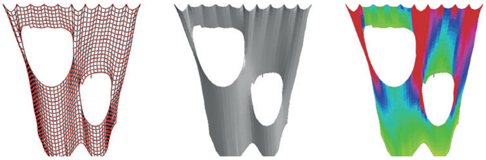

FIG. 1. A simple simulation of hanging cloth is visualized in three different ways. The left visualization shows the structure of the simulation, how the particles and springs are connected. The middle visualization shows the overall structure of the cloth and highlights larger deformations using the shading. The right visualization shows the magnitude of the forces each particle experiences.

student to modify the semiotic resource they create in any way they see fit (given the appropriate knowledge and ability) and, as a secondary effect, modify the affordances in any way they desire. This allows the student to create semiotic resources that allow the student to discern the specific affordances they aspire to discern. If a semiotic resource is not clear enough in its meaning, the student may modify it to create a new semiotic resource so the discernibility of a specific meaning-making affordance is increased, thus making it discernible to the student.

Within the multimodality framework [29,44], it is possible to change a representation by modifying it, or by re-representing it. If the change occurs within the same mode, such as rewriting a text, it is called a *transformation* [29]. If the change takes the representation from one mode to another, such as moving between formula and graph, it is called a transduction [29,32]. Social semiotics have adopted these terms and are using them to refer to different types of changes to semiotic resources. The importance of these changes or modifications can be understood from the variation theory of learning discussed below.

C. Variation theory of learning and programming

The variation theory of learning [38,45] states that to learn something, that something must first be discerned as its own aspect and to discern it, the student must experience variation about said aspect with respect to a static background. Marton [45] presented a good example about learning colors that highlights this. It is through the variation, compared to the static background, that the specific color stands out and can be discerned. Only by comparing to what it is not, can the color be identified as something it is. By varying the aspect a student should learn, that aspect becomes discernible and becomes possible to learn.

Programming allows for quick and easy variation among different variables and structures. By changing the mass of particles in a simulation, a direct effect can be discerned in the simulation. Perhaps the particle sinks, perhaps it floats, the change in mass will be discerned, experienced, and, potentially, understood. New questions may arise when old ones have been answered. Not just the variables can be changed, but also how the learner interacts with the simulation and how the simulation is represented. Programming provides ample opportunity, and quantifiable ways, to open up new dimensions of variation for the student and it also allows for the exploration of said dimensions of variation.

D. Programming as a tool for meaning making

Programming may be used as a tool for meaning-making in physics education in the same spirit as mathematics is used as a tool to investigate and understand physics. Through the act of implementation, the ideas and models of the students are made explicit and necessarily dissected into smaller understandable pieces that can later be joined together to form the whole model or idea. The pieces can also be modified, both internally and externally. Internal modification changes how a piece functions, for example, changing the interaction between particles. External modification means how the different pieces fit together, in what order they are placed and called.

The statement "Energy of the system is conserved" is an external piece, it gives information about how the system interacts with the outside world, but it does not give any information about the nature of the energy within it. The internal piece would describe the energy in the system itself, its potential, kinetic, thermal, or chemical energy and how they transform into each other. Programming provides the student with ways to explore both the external and internal parts of the concept they are implementing. They can explore which phenomena emerges and which interactions need to be explicitly inserted.

1. Example: The update() function

Within the particle class, created during session 2 of the workshop, is a function that updates the particles position and velocity based on the acceleration of the particle during each timestep.

In Fig. 2, the connection between position, velocity, and acceleration is made explicit by reading the code: The new velocity is equal to the old velocity plus a change in the velocity (acceleration) during the timestep. And the new position is equal to the old position plus a change in the position (velocity) during the timestep. The relationship between the concepts of position, velocity, and acceleration is made explicit and understandable through the use of programming. See Appendix B for an overview of the particle engine and the particle class used in the study.

E. Kolb's learning cycle

Programming's introduction of an iterative approach to physics modeling and understanding is well matched by Kolb's learning cycle [46]. Kolb describes the act of learning as a process where the student moves between

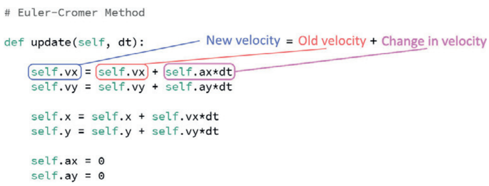

FIG. 2. The update() function of the particle class uses the Euler-Cromer method for integration. The connection between position, velocity, and acceleration becomes explicit when implemented into code. Velocity is used as the "changer of position during a timestep" and acceleration is used as the "changer of velocity during a timestep." The acceleration is calculated in a separate function, applyForce(), which extracts the acceleration from all the forces a particle experiences. The acceleration is reset between each timestep to avoid an "impetus-like" force.

different phases of the cycle. The different phases, in order, are as follows:

- Concrete experience and observation: Performing an experiment or having a realization.
- Reflection: Reflecting on the concept or observation and its connection to theory.
- Abstraction: Formation of abstract concepts and generalizations.
- Hypothesis: Testing implications of concepts in new situations.

The cycle moves from concrete experience to reflection to abstraction to hypothesis and back to concrete experience. As a student learns, they may enter this cycle at any point and move through the different phases as they learn about different concepts. Programming fits well into this cycle because the implementation of simulations often takes on this cycle, or iterative, approach. The act of observing the simulation provides opportunity for reflection: "Does it do as I want?", which in turn leads to abstraction: "If I change the constant to a linear term that depends on the distance…", which can then be tested using the program. The cycle can describe very large concepts that takes months or years to learn, or very small aspects such as learning the meaning of a for loop.

However, Kolb's learning cycle also provides a checklist of learning opportunities that should be provided to the students in order to facilitate learning. If the students do not have a moment to reflect on their observation, they will not progress to abstraction or hypothesis. Programming, in its very structure of implementation and testing, provides the opportunity for the student to move through Kolb's learning cycle at their own pace.

F. Summary of theoretical frameworks

Multimodality and social semiotics provide a language for talking about semiotic resources and how to modify them through different transformations or transductions. As code is implemented and simulations are visualized, the student moves between many different modes and performs many transformations and transductions with an obvious one being the transduction from formula into code and code into visualization. As the students construct their own simulations they create their own visualizations, or representations of the phenomena. The student-created representations then form a basis for explorations of the simulation through discernment and by interacting with using the mouse or keyboard. The interactivity and the discernment process provide the student with an environment where new questions may be asked and modifications to the code can be done to explore these new questions. Kolb's learning cycle describes this process well and it is through the use of variation (in the code, visualization, or by interaction) that new scenarios emerge that afford the student new meaning to understand and discover.

IV. RESEARCH QUESTIONS

The theoretical framework, described in Sec. II, and programming's potential synergy with said theoretical frameworks, provided us with some aspects that we have looked for in this study:

(1) How does programming help students to make predictions about their model or system?
(2) In what ways do the students create variation in the visualization to increase the discernibility of different aspects?
(3) How much programming knowledge do the students think is needed to use programming to explore and implement different physical concepts?

It is these learning predictions that make programming a potential tool for meaning making for physics education. However, the predictions are based on a proficiency in programming because a certain knowledge is required to perform the modifications. The study also aims to see how much programming knowledge is needed to extract meaning (about physics) from the simulation and to make changes to the simulation.

V. METHOD AND ANALYSIS

The study focused on qualitative observation of six upper secondary education students' actions and interactions with a workshop designed around creating physics simulations using the programming language Python [1] and using the Processing IDE [2]. The participants volunteered for the workshop after a quick visit to their class where the research and the workshop were described. The participants all came from the same physics-focused class and were familiar with each other. Students S1, S3, and S5 all had prior knowledge of basic programming for the workshops. S2, S4, and S6 knew about programming but had no practical experience. All the participants were between

17 and 18 years of age, half of them were female and half of them were male.

A. The workshop

The workshop consisted of five different sessions, each session was two hours long with a short break in the middle and the four first sessions were designed to introduce a specific part which was needed to implement a physics simulation and the last session was reserved for interviews and discussions. The code and details for the workshop are provided in the Zenodo database [47]. The structure of the workshop and descriptions of each session can be seen in Table I.

B. Data acquisition method

To obtain useful data from the students, several different activation methods [48] were used, such as peer discussions, code along, projects, and interviews. Each of these activation methods were designed either as a way to provide a new take on programming in physics, or as a way to extract information from the students by making them explain or discuss their ideas, problems, or thoughts. The whole workshop was video and audio recorded using high definition GoPro Hero 6 cameras and several Olympus WS-852 digital voice recorder devices. The students were also interviewed during the last session. The interviews were divided into single and group interviews and focused on open-ended questions. The questions can be found in Appendices A 1 and A 2 and are designed to provide the participants an opportunity to speak freely about programming, physics education, and the workshop as a whole. The group interview also included a problem, related to programming and physics, for them to discuss.

TABLE I. A list of the five different sessions of the workshop with the content of each session. During each session a different aspect is investigated or explored with the students. Each session builds on what was learned in the previous session.

Session 1	Introduce the notion of animation by incremental changes between frames and how to display different shapes on different locations in the window. Updating attributes between frames to introduce velocity and acceleration and ending the session with a ball bouncing in the window.
Session 2	Create a particle-class that is based on the code written in Session 1. The particle can show(), applyForce(), interact() and update(). The session ends with hundreds of balls bouncing in the window.
Session 3	Start with a group problem-solving session. The problem was: *"Create a model that replicates the simulation shown in here"* (Fig. 3). A model of the hanging cloth problem was then implemented which was based on the student's ideas.
Session 4	The students were asked to come up with a model for two-dimensional heat-diffusion and to implement it by themselves. The lecturer's task was to guide the students around potential pitfalls and help them with specific programming questions.
Session 5	Solo interviews as well as group interviews with the participating students. Questions for the interviews can be found in Appendices A 1 and A 2.

1. Peer discussions

The students were asked to come up with a model that would mimic the behavior of a simulation shown on the projector, see Fig. 3. The simulation was a model of a piece of cloth, hanging at the top of the display window and pulled down by a simulated gravitational force. The students could interact with the simulation using the mouse by pressing either the left mouse button or the right mouse button and dragging the mouse across the cloth, see Fig. 3. The students were divided into groups of three and asked to come up with a model, based on the particle simulation created in session 2, with the aim to model the behavior of the simulation. They had thirty minutes to come up with a model that would reproduce the phenomena discerned in the finished simulation. The students had papers and a whiteboard to discuss their ideas and the discussions were aimed to activate and increase their learning, but also to make them explain their thoughts to each other. The peer discussion exposed their problem solving process which was documented and analyzed. The discussions were audio and video recorded using one stationary camera per group and a mobile camera that could capture unexpected events not contained within the field of view of the stationary cameras.

2. Code along

The workshop used the new concept called *code along* commonly used in online lectures, see, for example, Ref. [49], where a small piece of code was coded live,

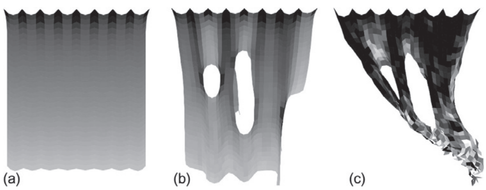

FIG. 3. A piece of cloth is simulated using particles that interact with the nearest neighbor with a force based on Hooke's law. The color shading represents how much a spring is elongated with light color representing small elongation and dark color representing long elongation. (a) A piece of cloth is hanging, only influenced by gravity. (b) The piece of cloth is cut using the left mouse button, the cloth reacts in real time. (c) The torn cloth is pushed around by the mouse using the right mouse button.

with the students, explained and explored. The code-along structure was designed to keep the students active and ensure an “I can do this myself” atmosphere by making the students write the code themselves, and by making sure that they got help when they made errors. During the code-along sessions, moments were devoted to explore the code, both in a guided scenario and by allowing the students to freely modify the code. In the instructed situation, the students were asked to vary a specific aspect and asked to observe how that variable affects the simulation. In the free situation, the students could change whatever they wanted, with the aim that the students would investigate some interesting aspects of the simulation. The students were video and audio recorded during the lectures, as was the lecture itself.

3. Project

During the fourth session the students were asked to come up with a model for heat diffusion, implement the model, and study the results. The students were encouraged to work in small groups, the same groups as in the peer discussion, to ensure verbal discussions and explanations. The project aimed to see how well the students could adapt the other parts of the workshop. The whole project session was video and audio recorded using two stationary cameras and one mobile camera, and several microphones.

C. Analysis

The analysis of the study was based on the recordings, visual and auditory, from the workshop, but also from field notes taken by the lecturer or researcher during the workshop. The aim of the analysis was to identify and analyze the student’s problem solving processes around the code, how they interacted with it, what they discussed, and how they approached problems related to the code and to the physics. Special care was taken when observing how they represented their models and their simulations and what changes they made to the code to create new representations.

The analysis uses a qualitative research approach, inspired by grounded theory and the constant comparative approach [50,51], that are currently being drawn on for educational interpretive studies (e.g., Refs. [52–54]), and aims to discover a theoretical structure related to the learning process of using programming in physics education. We use a cyclic approach by relating larger observed structures to smaller details and vice versa, which ensures a coherence of the underlying theoretical ideas that emerge. The videos were cut into smaller clips with the intent to extract interesting interactions or events that pertain to programming and/or physics learning or exploration. The clips were transcribed multimodally [44,55] and relevant learning structures were identified. This is an interpretive grounded theory approach, as discussed in Ref. [51], were the observed structures are interpreted using existing theories, such as social semiotics and variation theory. The extracted data was discussed and interpreted with experts within the physics education research field at Lund University. By iterating this process of identification and description, we eventually obtained a saturated description where all the interesting phenomena have been categorized, described, and organized by using a grounded theory framework in combination with social semiotics and variation theory; see Secs. III A and III C.

1. Representations

By studying how the students represented their simulations and how they choose to interact with them, it is possible to get a glimpse of what the student may or may not discern from the program. If a student changed how to visualize a simulation, it was because of some reason. That reason could be that the students wanted to highlight a specific aspect of the simulation, or that the first representation contained too much information and it was hard to discern anything because of all the clutter. It should be noted that the default representation in the physics engine displays a colored circle for each particle. This is often adequate in most situations, but if used to construct a gridlike structure, like in Fig. 5, it would quickly become cluttered and a new representation is better suited, such as using a wire-frame structure or filled parallelograms as seen in Fig. 3. Because of the instant feedback nature of programming, students may enter into an instant feedback loop, were they study their representation, change something they wish to highlight, study the new representation, change it again based on the new information, and so on. By observing this feedback loop, the students’ focus could be determined and how this focus changed during the loop, indicating that the students have learned something that made them shift focus.

2. Affordances

Affordances describe what a student discerns from a specific semiotic resource, or in this case, representation. By studying what a student discerns from a representation it is possible to obtain knowledge about their knowledge about the object from a certain discipline’s perspective. However, affordances will be used in a different manner for the analysis in this paper. The qualitative affordance analysis will look at what a student aims to discern and what changes the student performs to a representation to be able to discern that affordance. That is,

> *How does the student modify the semiotic resource so that the discernibility of specific affordances are changed?*

By looking at how students manipulate representations, a connection between what they perceive to be important, their relevance structure [38], and what the representation affords can be seen.

3. Extracting relevant student interactions

From the transcripts and from observing the videos, interesting discussions and interactions were identified and extracted from the mass of data by the first author, following the analysis method described above. Through discussions among the authors, interesting passages were chosen in such a way as to reflect the students' actions that pertain to both programming and physics. The chosen excerpts show different learning sequences by the student interactions among each other and with the code, such as figuring out a solution, asking investigative questions, discussions, the problem solving process of implementing the code, or creating a model. Data that are unrelated to these aspects were weeded out in the process, for example, when the students discuss what they plan on doing in their spare time. From the theoretical frameworks of social semiotics we know the importance of the interactions and discussions, but also how very small modifications may play a significant role in the learning process. We aimed to extract data that capture both situations.

It was also important to gauge the students' overall ideas about the workshop, programming, and physics, because their expectation, prior knowledge, and perception of the environment where the workshop and data collection took place will inform how they react to the content of the workshop. To extract this information we asked what they thought about the workshop and what programming proficiency would be required to participate in the workshop. This was done in the interview during session 5 using the questions found in Appendix A.

VI. RESULTS

The results presented here are seen through the lens of social semiotics and the parts that make up social semiotics, such as transductions, affordances, and semiotic resources. During the workshop, the participants performed a series of different activities and experienced different methods of activation. It is through these different activation methods and the qualitative analysis of the recordings and notes that the results have been constructed. The qualitative analysis identified the following aspect represented by the actions of the participants: transduction, variation, unpacking formulas, predicting, and iterating.

From the interview with the students, we found that the students were happy with the pace of the workshop and they thought the level of the programming and physics was good. Some commented on the need for basic programming knowledge to fully make use of the workshop, but that it was easy to follow the instructions. See Sec. VI E for more thoughts on the programming proficiency of the students. It thus appear that the setting, pace, and content of the workshop itself did not pose a hindrance to the student's ability to program or express themselves. Student comments are discussed in more detail in Sec. VI E.

A. Hooke's law

The students moved between different semiotic resources with relative ease when guided by a teacher. When writing the applyForce() the students implemented $\bar{F} = m\bar{a}$ and extracted the acceleration from an external force, $\bar{a} = \bar{F}/m$. During the implementation, they unpacked the formula and realized some information hidden in the notations and its structure; its two-dimensional nature and that the mass cannot be zero. The students followed along with the transduction from a formula to the implementation of said formula. In the third session of the workshop, the students implemented Hooke's law into code: $\bar{F} = -k\bar{x}$, where $\bar{F}$ is the force resulting from the displacement $\bar{x}$. The students had no discernible problems following the transduction presented in Fig. 4.

The transduction also highlights that there are two parts to $\bar{F}$, a magnitude and a direction. `dx` and `dy` from the code provides the direction and `F=-k* (le*—rest_le)` is the magnitude of the force.

B. Forces and $\bar{F} = m\bar{a}$

In the applyForce() method the applied force is converted into an acceleration and added to the current acceleration. The transduction highlights how to move from a force to a resulting acceleration. S1 commented the following on implementing forces on a simulation of a Frisbee, translated from Swedish to English:

S1: *For example, I just did a project with a Frisbee… and there I could go in and check… to see if what I had written by hand and implemented was correct. I had to think extra on the forces when I added them to the Frisbee.*

This implied that having to implement the formula into code, or performing the transduction, provided the student with a learning opportunity that had not been apparent before. Thus, the transduction of the force required the student to unpack the formula and identify its different parts to be able to implement it correctly.

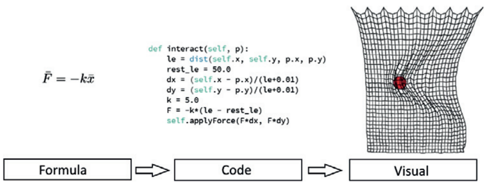

FIG. 4. Programming simulations requires transductions between different types of semiotic systems that each provide different meaning potential. To move between different semiotic systems requires the student to define the transduction explicitly and highlights each aspect of the system to the student.

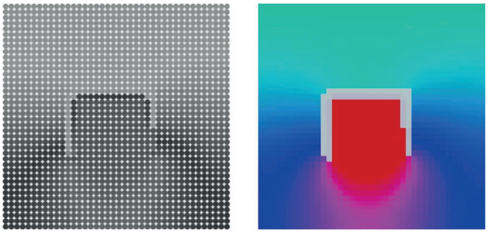

FIG. 5. S3 student started with the left visualization and modified it, in several steps, to end up with the right visualization. This is a recreation of the student's code and may differ in the precise final result, but the transition is the same—going from a black and white representation using circles to a colorful representation using squares.

C. Modifying the visualization

During the fourth programming session, S3 had managed to create a correct implementation of a heat diffusion simulation. However, S3 was not happy with the visual representation of the simulation and aimed to change it. See Fig. 5 for screenshots of how the visualization was modified. Programming provided S3 with the ability and the opportunity to modify a representation, something that books and static images do not provide.

Another student commentated on the ability to connect the visualization to attributes of the particles:

S4: *I made the temperature depend on… no, the color depends on the temperature. I placed self.t* [the temperature of the particle] *as the red color.*

As the student explained the idea behind the modification, they had to reflect on their implementation and understand how it works. The reflection is triggered by the student's requirement to match their explanation to their implemented model.

D. Internal modeling and predictions

Several of the students were able to make predictions of their yet-to-be implemented models and compare their predictions with the real world and/or other simulations. This shows an understanding and an ability to internally model the computer program in their heads, run it and compare the expected result with a reference as seen in sections VI. D. 1 and VI. D. 2.

The students' internal modeling and their ability to compare it with their models allow the student to iterate on their model. This was seen in the students' approach to implementing their models. By discerning how changes affected their model, an iterative process began, which allowed the student to get feedback from the model and adapt accordingly. The feedback loop also allowed the students to adjust their expectations or to understand parts of their model.

1. Heat diffusion

During the last programming session, the students were asked to implement a 2D heat diffusion simulation using the programming structure that had been produced during the previous sessions. As a student managed to implement a working model of the heat diffusion they exclaimed (translated to Swedish from English):

S5: *Yes!* [S5 puts their hands in the air] *It does what I want!* [S5 stands up to celebrate.]

The other students joined in with the celebration and could see that S5's implementation was correct. The realization that the simulation was correct came from a visual inspection of the representation S4 had coded. From the visual representation, S5 and the other students could discern that the implementation was correct, or at least reasonable. They did not need to see the code or how it was implemented, but only the visual representation of the program itself. The students were able to distinguish between an incorrect implementation and a correct implementation through the visualization itself and they could predict what a correct visualization would look like based on the expected behavior of their model.

The students then continued by examining the simulation closer:

S5: *It does what I want. So, theoretically, it will spread out.*
S3: *Ok, I'm coming to check… what have you done?*
S4: *Does it bounce against the wall?*

By observing the working simulation, new questions sprung up in their minds as they saw the thermal energy spread out among the particle: Would the thermal energy diffusion bounce at the wall? Questions that they, nor the lecturer, had not thought about before emerged and programming provided a way to answer them. The students entered into the positive feedback loop as soon as one step of the implementation was completed and began to investigate new aspects of the simulation.

2. Hanging cloth

During the group discussions in session 3, where the students were tasked with coming up with a model for a hanging-cloth simulation, see Fig. 3, the students discussed the forces in the cloth (translated from Swedish to English):

Gesture [S5 makes a gesture where two particles come together and pushes them apart]
S3: *No, it should not be a force outwards there.*
S5: *Yes, because they don't want to be together.*
S3: *It's not a slime, it is cloth. I can do this.*
Gesture [S3 takes part of their shirt and pushes it together into a ball shape.]
S3: *There is no force outward now.*
Gesture [S5 does the same with their shirt.]
S5: *Yes, if I release…*
Gesture [S5 releases the shirt and the cloth spreads out.]
Gesture [S3 releases the shirt and the cloth spreads out.]
S3: *Oh, it does spread.*

The students S3 and S5 were exploring the nature of the forces in a piece of cloth and how they would model it when the question became *"Does it have a force pushing out or is it only pulling in?* The question was resolved when S5 took a piece of their shirt, pressed it together into a small clump, released it, and saw that the shirt expanded. Through their arguments they identified a question in their model and used experiments in the real world to get an answer. The group had come up with a prediction of their model and tested it using the real world.

Another group did the same procedure, but instead of asking the real world for answers, they asked a simulation. From their own model, they made a prediction and tested the prediction using the simulation. In this case, the prediction was that the hanging cloth could not be pulled below its lowest point, since that would imply a springyness in the forces describing the cloth, something the group did not have in their model at this time.

S4: *Can you throw the curtain above?*
S1: *What?*
S4: *… is it possible to throw the curtain up completely?*
S1: *But it can go down, then it [the simulation] does not work if we can pull it down.*
S4: *Can you pull it down?*
S1: *It can be pulled down more than it is.*

Gesture [S1 uses the mouse to drag the curtain downwards.]

S1: *It can move down.*
S4: *That is a bit strange, maybe.*
S2: *Yes, but that would work here too if all* [the particles] *move.*
S1: *But, then it does not work…*
S2: *It can still work, they still move freely so that means that if they are on the sides from the start, they can move downwards.*
S1: *Eeh.*

The conversation continued about the model, but the main point is that the students interacted with the simulation, compared it to their yet-to-be implemented model and found that they differed in their function. It was also through the interaction with the simulation that they observed a phenomenon, the cloth being pulled and elongated downwards, that clashed with their own model. In this scenario, S2 realized that their model would be able to accommodate the new phenomenon, but S1 was not so sure.

Both groups made predictions about their models, found ways of testing their predictions, and updated their models based on the observation. The only difference was that one group used the real world and one group used a simulation to answer their questions. The students used both the virtual model and a real life model to make experiments from which they extracted information and drew conclusions.

As one group began discussing their ideas for implementing the cloth simulation, S2 dismissed the idea to use springs at first because it was not something they had experienced in the workshop. This mindset, to not use ideas or material from "outside," is seen in many educational settings and this workshop was no exception.

S2: *Like, if we define these particles to have two times the radius…*
S4: *Yes.*
S1: *What was it we did with the spring constant?*
S2: *I don't think it's relevant, I think we should use what we have worked with* [in the workshop].

However, S2 soon realized that using a springlike force between the particles may allow them to model the cloth and changed their perspective to include information from outside the workshop, such as their prior physics knowledge.

S2: *Can we not have a lot of balls sticking together.*
S4: *Yes, that is what I thought, we did something where we had a force that pulled two balls together.* [S4 is referring to a gravitational simulation as a test of the interact() method, implemented during session 2.]
S2: *Yes, and using the spring constant.*
S4: *Yes, maybe.*

E. Answers to interview questions

Here follows some selected answers to the questions about programming and physics and how they can or want to use it in their physics education. The questions can be found in Appendix A.

Question: What does programming give you, that you could not do in any other way?

S2: *…something else I thought about… that programming gives another angle on the physics. Often, you have exercises you have to solve, and that is the case in programming as well, if we would simulate a pendulum, but its much more… vague. There are different ways to do it. Instead of just solving something, you create.*
S1: *It has given me, that I can take a phenomenon or problem or … anything … from physics. Implement it and visualize it and … figure out answers and see if I've done it correctly.*

This student, S1, has seen that the physics engine created in the workshop can be used to simulate many different physical systems and scenarios. The ease of using the system and the feedback it provides, ensures that the student can discern and interpret the representation accurately.

S4: *… usually you just sit and calculate, there are no moving pictures and you can't interact with your calculations. But in this workshop you got to write your calculations in the form of code but you could also see how it worked in real-time so to say.*
S4: *It is as I said in the beginning. You get a chance to experience physics… I mean, you get the theoretical part but get to perform it… you get to see it in motion.*

The ability to see the equation in motion through an animation provided an extra layer of potential meaning-making compared to their normal physics education.

S1: *What I thought was good was, within physics, is… when we have worked, with forces, you have to think a little extra when implementing them into code… what directions. The good thing is that you get instant feedback if you've… if you've done it correctly or not.*

The instant feedback that programming provides, and the explicit nature of the code itself, gives the student a platform where misunderstandings and errors are easily discerned and corrected.

Question: What knowledge do you think is required to fully use the workshop—More programming?

S2: *I feel that for physics, you only need to understand physics, but here you need programming… at least the basics of programming.*

S1: *… If you haven't programmed before it'll take some time to get into the programming before you can get going with the physics.*

The sentiment, that an introductory course in programming was recommended in order to code and modify the simulations and use them for exploring physics, was mirrored by the other students in the group discussion.

The answers to the question "Can you explain the "Particle" -class?" was mixed but tied to the participants prior knowledge of programming. The students that had done some programming before could explain what the different functions did with greater confidence than the students that had no prior knowledge of programming. However, even students with prior knowledge could not fully recall exactly what the functions did. This lack of knowledge is attributed to the short time the students interacted with the program.

VII. DISCUSSION

The theory of social semiotics combined with the data gathered from the workshop have shown that the theory predicts what affordances programming exhibits and that the students were able to discern and use them to explore the physics phenomena at hand. From the analysis of the programming experiences by the students, indications of a richer use of programming for learning physics can be seen, especially if the students themselves are allowed to create and implement their own models.

- students were capable of creating, implementing, and extracting meaning from physics simulations.
- students with no prior knowledge of programming could implement their own models when guided by a teacher.
- students with some prior knowledge of programming could implement their own models without guidance from a teacher.
- students recognized their own ability to program and suggested that an introductory course in programming, which half of them had taken, is all that would be needed to make use of the programming in the workshop.
- some students highlighted that programming provided another approach to physics education compared to their traditional educational setting.

Students entered into a feedback loop as they tried out different variants of their code or model, discerned the result, and modified their code or model. In every step of the implementation of the model, the students have asked questions of the real world, completed simulations, not-yet-implemented code, and half-implemented code. The answers they received made them change the implementation or model. Either it was an error in the code, a typo, or a thinking error, a "thinko," that made them reconsider and change. Programming forces the student to reconsider their models until a functional model is produced.

Students could and did ask questions about their program, model, or implementation, interpreted the answers, and adapted their model. This process is the learning process as described by Kolb in his Learning Cycle [46]. Students changed the resulting semiotic resources to increase the discernibility of specific meaning-making affordances. The students interacted with the hanging cloth simulation to see if they could increase the discernibility of a certain affordance: "springy-ness." During their investigation they discerned a phenomenon they did not expect: The cloth could be elongated by dragging it, and they had to adapt their model.

Another student changed how the heat diffusion was displayed by changing the shapes of the visualization of the particles from circles to squares to reduce the clutter and thus increase the discernibility of relevant affordances such as the temperature distribution and the temperature gradient.

A. Modifying the affordances

The students interacted or modified the resulting semiotic resources to highlight different aspects, or, to make certain affordances more discernible. When the students interacted with the hanging-cloth simulation, they were unable to discern a specific affordance that would answer their question until they had changed the simulation by pulling on the cloth. The resulting animation then offered the students another set of affordances or made a specific affordance discernible. Specifically, the students used the mouse to interact with the simulation to see if they could pull it downwards, this specific aspect could not be discerned unless they interacted with the simulation. The interaction provided a new scenario where the students could discern that the cloth could be dragged down, but that it could also be pushed up above the attachment points. The new scenario answered one question but created a new one. This use of variation is well described by the variation theory of learning [45].

It is through changes and investigations that answers to questions can be obtained. As the students create new simulations, new questions will arise that they wish to answer. To answer these questions, they will modify the semiotic resource they are interacting with, creating a new semiotic resource that provides the ability to discern the needed information to answer the new question. Social semiotics [24,25,27] and its semiotic resources are a great way of explaining the ways in which programming can be used to modify and create new semiotic resources that enhance the learning of physics.

B. Programming as a means for meaning making

Thanks to programming's ability to easily and quickly modify different aspects of a simulation, students can open up many different dimensions of variation to explore. The quick and easy exploration that programming provides allows the student to investigate and eventually understand how different aspects relate to each other and how they affect different parts of the simulation.

1. Forces and programming

Forces are an important but hard [56] concept to grasp for a learner. Forces can have many different sources but they all sum up to a net force which will describe the acceleration of an object. A force has two components, a magnitude and a direction, and this may be hard to grasp because both aspects are usually baked into the vector notation used to describe them. In programming, we can choose to make the two components explicit, as can be seen in Fig. 4 and in the answers given in Sec. VI E.

Programming is well suited to take advantage of the variation in the variation theory of learning thanks to its digital and repeatable nature. By changing a single variable in the code and observing the changes, the student is made aware, in an interactive manner, of critical aspects and can modify these to observe changes in the simulation.

Programming offers a wide range of possible transductions. One is transductions that take one semiotic resource from a semiotic system to another, such as going from a formula into an animation. The transductions performed when programming are explicit transductions where each relevant aspect has been considered and taken into account. The explicit transduction is done by the student, and each aspect is laid bare for the student to explore and investigate at their leisure. One explicit transduction can be seen in Fig. 2, where the transduction from mathematical integration is written in code, requiring the student to explicitly write the relationships between position, velocity, and acceleration.

Programming allows for quick and easy changes that affect the affordances of the semiotic resource produced by the code, either by changing the code or by interacting with the semiotic resource itself. New scenarios can easily be created and new aspects can be discerned from the new scenarios. Each student can create semiotic resources that are tailored to their individual questions and ability to discern. Programming thus allows for a wide dynamic range of affordances, some that will greatly enhance the possibility for meaning making and some that may detract from the meaning-making experience of the student.

By using a guide (teacher) when programming, relevant affordances can be made more discernible and students can get a powerful tool to use when investigating and constructing different models of many different physical phenomena.

VIII. CONCLUSIONS

We found that the theory of social semiotics in combination with variation theory can be used as a new way to describe and understand the usefulness of programming as a tool for meaning making in the physics classroom. The students in this study were able to successfully use programming to create simulations and use the process of creating and implementing models as a means for meaning making about different physics concepts.

As students developed their own models, they were able to test it at every step of the implementation. To test their programs, they needed to perform mental modeling to compare with the visualizations; programming helped them test their predictions and modify the system accordingly (RQ1).

To better highlight disciplinary relevant aspects, students modified the shape, color, and location of their visualizations. (See, for example, Fig. 5.) We found that the students could modify the visualizations in ways that enhanced their learning experiences by taking ownership of the visualization process (RQ2).

The students expressed that some prior knowledge of programming was needed to take full advantage of the programming sessions. However, the students without prior knowledge said that they could follow along without difficulty, but they could not as easily implement their own ideas (RQ3).

The theoretical framework illustrates the possible interplay between the semiotic systems: coding, interaction with the simulation, and visualizations. In this study we found that the iterative nature offered by programming facilitates productive transductions between these semiotic systems.

This work gives a few examples of how programming can be used to enhance meaning making in physics education. In a next step, we are offering professional development for teachers to learn the programming method. Their experiences and reflections on opportunities in classroom implementations, as well as difficulties encountered or expected, are captured through follow-up interviews.

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APPENDIX A: INTERVIEW QUESTIONS

During the interview session the students were interviewed one by one with the questions in Sec. A 1, but their discussions where also studied during group interviews. The questions used in the group interview can be found in Sec. A 2.

1. Solo interviews

After the workshop, the students participated in solo interviews with the questions, translated from Swedish to English:

1. What do you think about the workshop as a way of learning physics?
2. What do you think you learned during the workshop?
   • What was good, bad, easy, or hard?
   • What knowledge do you think is required to fully use the workshop?
     — More physics?
     — More programming?
     — More tasks?
     — More demonstrations?
3. Can you explain the “Particle”-class?
   • Explain what the different functions do:
     — __init__()
     — show()
     — update()
     — interact()
   • What can they be used for?
4. What is it that programming gives You, that You could (perhaps) not do in any other way?

2. Group interviews

After the solo interviews, all students that were present for the final session participated in a group interview about the workshop. The interview aimed to start discussions among them to see if they could draw upon their programming experience to identify solutions and/or problems. The group interview questions, translated from Swedish to English:

1. What do You think are the pros and cons with programming compared to normal lectures in a classroom?
2. What do You think are the pros and cons with programming?
3. How do You want to or can use programming in physics?
   • What role does programming play in physics research?
4. (For Researcher): How do they use their computational thinking when analyzing the physics problem:
   • If You were to create a simulation of two colliding galaxies, what would you do?

APPENDIX B: THE PARTICLE ENGINE

The physics engine constructed by the participants during the workshop was based on the grid-free method of a particle based physics simulation. The particles are described by their own class with the following methods:

• __init__(x, y, mass, radius)
  — Initializes the particle with some attributes and values. This method is required by Python to initialize any object. This method is used to set initial conditions or default values for attributes of the particle. The particle always have position, velocity, acceleration, mass, and radius to make the other methods work. Other attributes are added by the programmer.
• show()
  — Displays the particle in a window. The default visualization is just a circle with a static color. The user can change how the particle is visualized by modifying this method.
• update(dt)
  — Updates the attributes of the particle using an Euler Cromer [57] integrator. The implementation can be seen in Fig. 6. The update method calculates a change in velocity using the acceleration, which in turn is also calculated by each timestep. The velocity is then used to calculate a change in position. The method is designed to explicitly show how the attributes are updated in each timestep and avoids some simplifications that can be made.
• interact(other)
  — Handles the interaction between particles. It then applies the resulting force on the particle using the applyForce() method. This is the main method that deals with different physical models such as gravitational interaction, Hooke’s law or any other interaction between different particles.

```
def update(dt):

    self.vx = self.vx + self.ax*dt
    self.vy = self.vy + self.ay*dt

    self.x = self.x + self.vx*dt
    self.y = self.y + self.vy*dt

    self.ax = 0
    self.ay = 0
```

FIG. 6. The implementation of update(dt) avoids the use of vectors or syntax that could make it simpler. The aim of the function is to explicitly show how the attributes are updated during each timestep. During each timestep, new forces are calculated and a net acceleration is obtained, the old acceleration must be removed, to avoid an impetuslike effect.

- applyForce(fx, fy)
  — Add all the forces together and calculates a net acceleration using $F = ma$ rewritten as $a = F/m$. The method is called from the interact(other) method and is the primary way the user interacts with the particles.

The particle class and its methods are used in the draw loop, built into the processing IDE, to update and show the particles. See Fig. 7 for an example of the simulation loop. During each iteration, each particle interacts with all other particles, it then feels a force downwards (gravity), updates its position, and displays itself in the window.

The loop and the methods and the names of the methods are chosen in such a way that they are easily understood and each part has a well-defined purpose. Using this setup and the methods, it is easy to identify the different parts needed to implement the simulation and what parts are required to have a functioning simulation.

```
def draw():
    background(234)

    for p1 in particles:
        for p2 in particles:
            p1.interact(p2)

    for p in particles:
        p.applyForce(0, 9.81)
        p.update(dt)
        p.show()
```

FIG. 7. The loop that is iterated over each timestep of the simulation. The particles all interact with each other and then they update their position and show themselves in the window. draw() is called as fast as possible, or as fast as the display allows, which is usually around 60 times per second.

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Paper III

Review Article

Concept of a transductive link

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This theoretical paper defines and explores the concepts of transductive links and transductive chains, as part of the theoretical framework of social semiotics. Social semiotics stems from the multimodal framework, which provides a theoretical perspective, constructs, and a language to describe a shift of semiotic material within or between semiotic systems, such as rewriting a text or moving from a function to a plot. Within this framework a shift of semiotic material between two such systems is referred to as a *transduction*. This paper aims to expand on the concept of transduction by identifying a theoretical contribution to the modeling of this process, referred to as a *transductive link*. This link is suggested to affect the transduction process and the resulting learning experience. For example, when plotting measurement data, a computer program can be employed to read the data and to transform the data into pixel information. In this case, programming, or the act of programming, acts as a link between the two resources in the transduction process—a transductive link. In other cases, multiple transductions can be performed one after another resulting in these links creating what we define as a *transductive chain*. By observing and analyzing the use of different semiotic systems in different learning situations, transductive links and chains can be identified and examined. From this identification one has the possibility to find weak links in the transductive chain and address them accordingly. As such, we suggest that transductive links and chains are powerful tools to be able to understand students' learning experiences.

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I. INTRODUCTION

This is a theoretical paper, building on empirical work, that aims to expand the theoretical framework of social semiotics and multimodality by discussing the concept of a transductive link. This concept provides a descriptive term to be used in the analytical process of learning situations, but also as a way of scaffolding and varying the transduction process in the classroom, which in turn may lead to learning outcomes.

A. Transductions and physics—examples from the discipline

Physicists constantly use different methods and scientific processes to analyze and investigate different phenomena. In this process, various types of representations are used to discover and enhance different aspects of the phenomena. In this paper we will discuss this using a well-known example from astrophysics: the Hertzsprung-Russell (HR) diagram. An astrophysicist investigating stars and the stellar life cycles is probably going to construct a HR diagram of newly obtained data as part of the analysis process. The process of arriving at this diagram requires a number of precise steps—record data from stars, perform statistical analysis on the data to weed out errors, organize and categorize the data, and finally visualize the data using a scientific visualization tool. Figure 1 showcases some of these steps. Each step requires some expert disciplinary knowledge to perform, such as programming the satellite, constructing the detector, or performing the statistical modeling. Any astrophysicist aiming to fully understand the nature of the stars is required to understand these steps in full. The astrophysicist must understand how the signal from the stars have been manipulated to get a full understanding of what the final representation—the HR diagram—actually represents. These steps are within physics education research (PER) known as *transductions* [1–5] and describe the process of moving from one type of representation to another—such as moving from the data to the visualization. Similar processes, i.e., transductions, are ingrained in any physicist's work to investigate and understand different phenomena and, similarly, must also be part of the learning process for students. A student must learn how to move between different representations as part of their path towards understanding. Transductions have also

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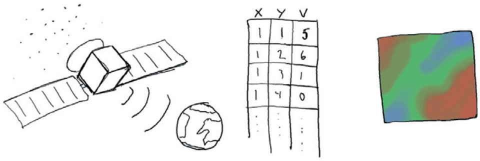

(a) (b)

FIG. 1. (a) Light from the stars is detected by the satellite and sent back to earth as digital signals. (b) The data is converted into an image that is designed to allow the physicist to see and understand certain aspects of the stars.

been shown to play an important role in physics students' meaning-making process; see, for example, Refs. [3,4], and, in particular, Ref. [6] for pertinent examples concerning the unpacking of the HR diagram versus its disciplinary and pedagogical use.

A step that students must understand in order to understand the connection between phenomenon and formula is the step from a laboratory activity to a formula or plot. They must understand how a specific apparatus records the data, how the data are manipulated, and how the data are related to the formula. When students measure the gravitational acceleration using a ticker-tape setup, see Fig. 2, they must understand how the ticker works, why the dots are spaced out, and how to move from the dots to the formulas for velocity and acceleration to determine the gravitational acceleration. This is an example of where a physical concept is transducted using the ticker-tape setup. The laboratory equipment allows for the discernment of a specific aspect of gravity using a certain technique and filters out other aspects. In Fig. 2 the different transductions are measurement → calculations → formula → graph. Each step in the process requires the moving, filtering, and manipulation of semiotic material.

With these examples, we have now highlighted what the normal process of doing and learning science entails.

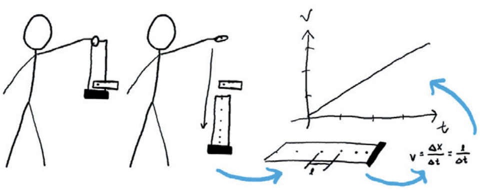

FIG. 2. A tape with a weight is dropped through a ticker. The ticker marks the tape at regular time intervals as the tape falls. The student must then connect the distance between the dots on the tape to the notion of velocity and plot the velocity. From the slope of the velocity in the plot, the student may then calculate the acceleration. These steps are all examples of different transductions.

However, and as we will see, the process of moving from one way of representing information, using a particular semiotic system, to others, has not been addressed properly previously in the social semiotic framework for physics education. Using the concept of transduction, we will thus provide a concept for how these changes can be theoretically described as links and chains, hence contributing to the theory of social semiotics.

II. BACKGROUND

The process of transduction has been identified as an important process for students to master as they move towards fluency in the physics discipline [3,4,7]. Several theoretical frameworks address this process and take their own view on it [8–10]. Transduction in the way that we use it in this paper stems from the multimodality framework [11,12], a framework which describes how meaning making takes place using several different *modes*, where a mode is, for example, speech, text, images, gestures, or any other distinct way of representing a concept. By combining modes, such as using text and images in a book, multimodality aims to describe and provide an enhanced learning situation where students move between different modes. Each mode aims to highlight or present certain aspects of the whole concept and it is the combination of modes that provides the student with the opportunity for simultaneous discernment of the different aspects of the concept. Within each mode a concept is represented using that mode's specific attributes. A physics concept may be described in words, as an image, or even an animation, where each of these is a representation of the concept, but each representation holds different potentials for meaning making, often referred to as *disciplinary affordances* [6,13,14]. For example, using the ticker-tape example discussed earlier, the dotted paper strip captures certain aspects of the concept under study, the table created from measuring the data points holds other aspects. The same is true for the graph created from the table and the final formula created from the slope of the graph. Each one of these representations in itself is not enough for fully understanding the phenomenon, but together they create a whole that enhances the possibilities for meaning making by the student.

Social semiotics is a multimodal theory but adds the social aspect as an important aspect of the learning process. Instead of only talking about representations, social semiotics talks about semiotic resources. A semiotic resource is any resource that is used to communicate meaning, such as activities, tools, and representations [15]. Social semiotics studies the meaning-making of specialized groups in society, such as how physicists communicate and make meaning as they discuss and investigate different physical phenomena. Social semiotics, building on the multimodal theory, has taken on the language of multimodality and is using the term "transduction" to mean a shift from one

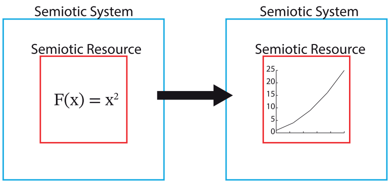

FIG. 3. The transduction process, shifting the semiotic material from a semiotic resource (red) by constructing a new semiotic resource in a new semiotic system (blue). We aim to expand on the description of the arrow (the transduction process) by the theoretical concept of the transductive link.

semiotic resource to another, but also a shift from one semiotic system to another. A semiotic system can be seen as a mode from multimodality, and shifting between different systems is the same as shifting between different modes [5,16]. In Fig. 3 we see a very common transduction, namely, the shifting from a formula to a graph. This transduction is described in social semiotics as a shift of semiotic material from a semiotic resource in the semiotic system "formula" into a new semiotic resource in the semiotic system "graph."

However, the process of transduction may be performed between many different semiotic systems and each type of transduction is possibly different compared to any other type. For example, going from a text to a formula is different compared to moving between a formula and a graph. To only describe these different types of transductions using a single word does not capture the breadth of the different types of transduction processes that exists, nor how different transductions may differ. An expansion and understanding of the transduction process is required to be better able to understand the affects and aspects of different transductions.

Transductions are useful tools to showcase a concept in a new way, for example, by drawing a graph that represents a function. This new way of presenting the information contained in the function may change how the students understand the information and the relationship it has to the situation or the discipline. This change in how a person sees and understands a concept is referred to as *conceptual change* [17–21] and attempts to capture the idea that the understanding of concepts and relationships changes over time as new information and new ways of thinking about it are experienced. By better understanding transductions and its potential role in the conceptual change process, one can get a better understanding of the learning process. Transductions should also be performed by the students as part of their own problem solving and investigation, as they, in the process, necessarily must construct their own representations of the concept. Student created representations have been studied in Refs. [8–10,22] as part of the learning process.

A. Different ways to represent a concept

In Ref. [7], Airey and Linder describe what they call a "multifaceted way of knowing" a concept. They say that a concept has several ways of being experienced or investigated, such as representing the concept as a formula or as a graph. The different ways of representing the concept provide access to a different facet of the concept itself. They go on to argue that a concept requires a multifaceted way of knowing it before it can be fully understood, i.e., no single representation can convey *all* the information needed to fully present the concept in question. By representing the concept using different semiotic systems and resources, different facets of the concept can be presented and offer discernment of new aspects of it. However, Airey and Linder also describe a secondary aspect of their construct—a link—which aims to connect two different semiotic systems. This link is later referred to as a "transductive link" in [15]. In Fig. 4, the semiotic system "diagrams" acts as the transductive link between "experimental work" and "mathematics." The blue lines in the figure represents a shift between semiotic systems, or a transduction, and the red lines represent a semiotic resource representing the concept. In reality, a concept has many more facets than the six shown by the hexagon in Fig. 4 and there may be many facets that we do not have access to given the semiotic systems we are currently using. However, although the term transductive link is used in Refs. [5,15,16], it is not rigorously defined nor explored.

We claim that *how* a transduction is performed will have an impact on the meaning-making process; there is a difference between seeing the initial and final semiotic resource compared to understanding the path between them. A transductive link is experienced by the learner and connects the initial and the final semiotic system. We would also like to stress that we are only looking at the actual semiotic resources themselves and what they afford,

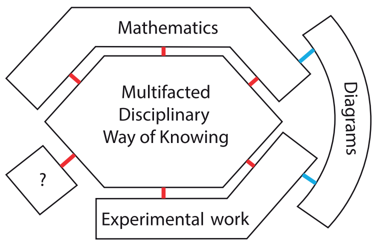

FIG. 4. A concept is experienced using different semiotic systems and many of the concept's facets are revealed through the different types of semiotic systems. Diagrams are used as the transductive link between experimental work and mathematics. The blue lines represents a shift between semiotic systems and the red lines represent a semiotic resource representing the concept. Adapted from image found in Refs. [7,15].

as well as how this changes as part of the transduction process. Thus, in this paper, we are not making any claims about students' understanding of a particular transduction process.

The aim of this paper is thus to define and explore the concept of *transductive links*, introduce *transductive chains*, and to exemplify how these links and chains can be used in both physics education and physics education research to better teach, understand, and analyze students' meaning-making processes.

III. TRANSDUCTIVE LINK

Although introduced in Ref. [15] and later used in Refs. [5,16], no formal definition of a transductive link exists. By building on the description of transduction in Ref. [12], where transduction is described as "the movement of semiotic material from one mode to another," we can construct a definition of a transductive link in a social semiotic setting:

> *A transductive link is any semiotic system that supports the transduction process between two different semiotic systems.*

The word "support" is chosen in this definition because a transductive link and its implementation may come in many different forms and different transductive links will affect the semiotic material differently. Thus, the word support captures the effect and intent of the transductive link. A transductive link should support the transduction and make it, or the semiotic material itself, easier to discern. For example, by using gestures to indicate how a function can be drawn in a graph, we employ the semiotic system of "gestures" to support the transduction process. The gestures will affect the transduction process and help the learner discern new and important aspects of the situation, such as making the connection between a point on the graph and the evaluation of the function but also how to construct and read a 2D graph.

A semiotic system becomes a transductive link when it is employed with the purpose of supporting the transduction process. Thus, we need an initial semiotic system and a final semiotic system to be able to define a transduction and its transductive link. However, this also allows us to break down the transduction into smaller pieces by stating that the transductive link is our final semiotic system. There is now a transduction from the initial semiotic system to the old transductive link and between them we may find, or use, another transductive link. This reduction will come to an end when no new semiotic system can be found to be a transductive link. Remember that a semiotic system must represent the concept in a qualitatively different way. If we just keep dividing the transduction into smaller steps, we will eventually end up with a change that cannot be described as representing the concept in a qualitatively different way and because of this they are not transductive links.

In another example, Svensson *et al.* [5] identified programming as a potent transductive link where students created their own simulations of different physical concepts. During the implementation process the students had to unpack and understand the different aspects of the physics involved (semiotic system: formulas) and construct new representations of the physics (semiotic system: interactive simulations) using programming. Figure 5 shows a theoretical example of how a transductive link (programming) can be used to go between two different semiotic systems (here a formula and a graph). In the case of programming, the transduction process is supported in the sense that the use of programming facilitates the entire process and is not a simple addition, such as a gesture, to the process.

As discussed above, the construction of an HR diagram requires a transduction to move from the light emitted from the stars to drawing the diagram. Depending on how the data are processed, and the intent of the usage of the HR diagram, different transductive links may be chosen to be part of the transduction process. In the example from the introduction, with the data and the final visualization, programming is used as the transductive link. However, the HR diagram may be constructed without the actual data by an experienced instructor. The instructor may choose to draw the HR diagram on the whiteboard and qualitatively showcase the structure of the diagram, or they may show it in a textbook. In these cases, different transductive links will be used and the resulting semiotic resource will be different with different qualities. In Fig. 6 two different HR diagrams have been constructed using the same data but with different intent. One diagram is designed to showcase the use of an HR diagram and shows a small subset of representative stars while the other has grouped stars together and shows them as circles. The circle radius is an indication of the variability in the absolute magnitude of the star itself. In both cases, programming was used as the transductive link, but how it was applied differed depending on the intent of the final semiotic resource.

A. Transductive chain

The definition of a transductive link, which we suggested earlier in the paper, allows for the use of several links in the transduction process. We suggest that when several links are used together to support the transduction, this

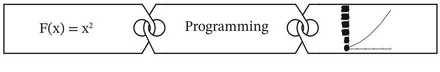

FIG. 5. Programming acts as the transductive link between the mathematical function (semiotic system: formulas) and the semiotic system graph. Here, it is through the use of programming that the transduction takes place.

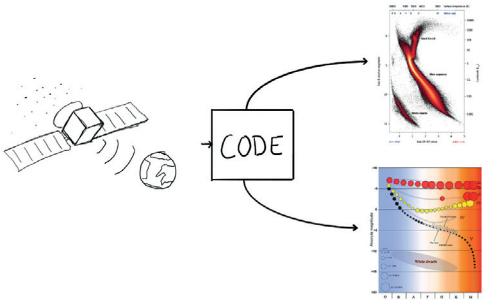

FIG. 6. The same data are captured using satellites and used in a program to construct two different HR diagrams. Depending on how programming is applied will affect the outcome. The top diagram is from the GAIA project [23] and showcases four million stars. The bottom diagram showcases groups of stars and their variation in absolute magnitude is coupled to the size of the circles. The bottom diagram is reprinted, with permission, from Ref. [24]. Both diagrams were constructed using data from satellites and by using programming to visualize it. Using the transductive link, programming, two different semiotic resources were constructed from the same data but they aim to showcase different aspects of the data.

combination forms a transductive chain (Fig. 7). A transductive chain may be composed of just a few links to form a short transductive chain, or it can consist of many different transductive links in a longer chain. A long transductive chain could be a physics project in class, where the project starts with a problem statement and ends in a report or presentation (the in between transductive links are, for example, laboratory equipment, diagrams, mathematics, speech, gestures, text). This whole project can be seen as a transduction from the stated problem to the report through the use of a chain of transductive links.

A transductive chain may be built up over time as new insights are obtained through different transductions. At the end of a transduction process, the initial semiotic material has been shifted to a new semiotic system with the construction of a new semiotic resource in that system. This new semiotic resource may provide new insights or ideas for further study or experimentation, such as if measured data do not line up with theoretical predictions, which then triggers the development of new models and theories. The new semiotic system is used as the transductive link for taking the next step in the exploration process, thus extending or creating a transductive chain.

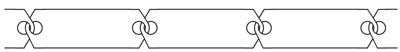

FIG. 7. A transduction can often be divided up into several transductive links, as seen in the figure, forming a transductive chain.

We suggest that this process of expanding the transductive chain by using a previous semiotic system as a stepping stone in the shift towards a new semiotic system (and a new semiotic resource) allows us to theoretically describe the flow of semiotic material in different learning situations.

Once again, to construct the HR diagram, it may be necessary to perform several different steps, e.g., obtaining the data from the satellite, performing different statistical operations, obtaining new values from it through different formulas and visualizing the data in the diagram. This would be an example of a transductive chain, where several links are employed after each other, or at the same time, to produce the diagram. The HR diagram may not be the end of the chain. Instead it may just act as a stepping stone to another semiotic resource which is better suited to understand a new phenomenon that could only been seen in the HR diagram. The HR diagram may only be there to provide some insight and this insight sparks the creation of a new diagram, simulation, formula, or paragraph in a chapter. In this case, the HR diagram acts as a transductive link for this new semiotic resource. It should be noted that any semiotic system is intended to become a transductive link to another one. Any new insight gained from the semiotic resource should trigger further exploration into the new thought and will require the construction of new semiotic resources. The GAIA satellite data was plotted in a HR diagram, and new, or unexpected, structures were found in the distribution of white dwarfs which lead to further research (see, for example, Ref. [25]). The HR diagram became a transductive link in the transduction process for new research after new insight had been discerned in the diagram.

IV. DISCUSSION AND IMPLICATIONS

Below follows a discussion of the use of transductive links as well as implications based on and around the concept of a transductive link. Suggestions of how transductive links may be used to inform and understand different learning situations are given and examples of transductive links from research literature are highlighted. By giving enlightening examples of how to approach and use transductive links in research, or in teaching, we believe that the concept itself can provide a new way of thinking about, and approaching, different learning situations in physics education.

A. Transductive link as a descriptive term for analysis

In qualitative physics education research it is often required to analyze different learning scenarios and create rich descriptions of the students' interactions and discussions. This rich description then acts as the basis of the analysis of how to interpret and improve the learning situation. By identifying any transductions or transductive links used by the instructor(s), or the students, the description of the data becomes richer and more detailed, see

Sec. IV C for examples of transductive links in research literature. One way that the richness of the descriptions can be increased is by the potential of forming categories of transductive links.

1. Categorization of transductive links

When transductions or transductive links have been identified, a possible further step in the analysis process is to categorize different transductive links—also their uses—into categories. For example, programming could be used as a transductive link in both a pedagogical and disciplinary way, depending on how it is applied. As described in Refs. [6,14], a single semiotic resource may have different pedagogical and disciplinary affordances depending on how it is used. The same is true for transductive links; depending on how they are applied, they will afford pedagogical or disciplinary aspects; this can be seen in Fig. 6 where the same transductive link is applied with different intent. In two different papers, Svensson and colleagues demonstrated, both practically [16] and theoretically [5], how programming may be used as a transductive link to increase the pedagogical affordance when learning about Newton's laws of motion. They also argue for how programming may be used to increase the pedagogical affordances, both of programming itself, but also of the semiotic resources that are created using programming. To increase, or to use programming with a pedagogical intent, the authors argue that the students, and instructors, should use programming's ability for quick and easy iterations to explore and vary different aspects of the simulation but also programming's ability to construct precise visualizations based on hidden data such as visualizing "temperature" as a color. When these aspects are used to explore and understand different physical concepts, such as the connection between position, velocity, and acceleration, we say that programming is used as a transductive link with pedagogical intent. Whereas in Ref. [25] programming is used with disciplinary intent and aim to highlight different disciplinary aspects of HR diagrams so that any discrepancy between data and theory can be identified.

Further, each transductive link will also have some inherent aspects that affect the transduction process. For example, the programming of a simulation allows the possibility for easy quantitative manipulation of numbers, whereas a drawing on the whiteboard allows for quick and easy exaggeration of different qualitative aspects. The various inherent aspects of a transduction can be seen in Ref. [16], where programming, through an update loop, was used to showcase the relationship between position, velocity and acceleration. The first program in Ref. [16] produced a simulation where a ball appears to fall down with an accelerated motion and this visualization allowed for discernment of what the relationship between position, velocity, and acceleration in the update loop actually means. The code for the simulations can be found in Ref. [26]. This type of discernment may be much harder if the student was presented with a static image or only formulas (see, for example, Refs. [27–30] for studies using animations as learning tools in science education) or, as Ref. [7] describes it: the animation offers discernment of a new facet of the concept.

Transductive links can thus be categorized both in how they are used, but also with respect to their inherent affect on the transduction process. These categories provide a meaningful description of the situation. Instead of just saying "… the data were transducted into a graph…" we can now say "… the data were transducted into a graph using programming as the transductive link with the intent to showcase X…" The intent of the transduction and the transductive link affect the final graph and how the final graph may be used and both need to be presented to fully understand the affect of the transduction itself.

2. Disciplinary and pedagogical uses of transductive links

As Volkwyn *et al.* [3] argued, a transduction acts as a filter and as a highlighter for different disciplinary relevant aspects, such as extracting the intensity of a signal, while not taking the polarization or angle of the signal into account. The purpose of a transductive link is thus to extract and filter the information in the intended semiotic material in order to highlight some chosen aspects. A similar effect is described by Fredlund *et al.* [14] as part of the unpacking process of semiotic resources. Unpacking a semiotic resource is the act of stripping the resource down to its disciplinary relevant aspects and highlighting only a few, or only one of them, in a pedagogical manner. Here we can see that the act of transduction is very close to the act of unpacking with the difference being that an unpacking does not require a shift between semiotic systems. However, we can say that within a transduction exists the act of unpacking with the added element of constructing a new semiotic resource in a new semiotic system and that the transductive link must help facilitate the unpacking.

In a teaching and learning situation, a teacher will most likely use transductive links with pedagogical intent and aim to construct a new semiotic resource with higher pedagogical affordance than the originally used resource. On the other hand, a researcher, or a disciplinary expert, may use the same transductive links to construct a semiotic resource with high disciplinary affordances, as seen in Fig. 6. When transductive links are used in these ways, it can be argued that they are used to "unpack" the initial semiotic resource. In Ref. [6], the authors describe this unpacking in an example to provide a higher *pedagogical affordance* (see below) (see Fig. 8 for a schematic representation of the unpacking process). The unpacking of a semiotic resource will take on different characteristics depending on what transductive links that are used and may thus change the resulting pedagogical affordances of

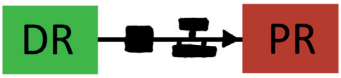

FIG. 8. A semiotic resource with high disciplinary affordances [disciplinary resource (DR)] is unpacked to construct a new semiotic resource with more pedagogical affordances [pedagogical resource (PR)]. The unpacking of the semiotic resource may be done using different transductive links, either as complete steps or as scaffolding, if the unpacking requires a transduction.

the new semiotic resource. Airey and Eriksson [6] (p. 1–2) use the following definitions of disciplinary and pedagogical affordances:

Disciplinary affordance: *the agreed meaning making functions that a semiotic resource fulfils for a particular disciplinary community.*

Pedagogical affordance: *the aptness of a semiotic resource for teaching some educational content.*

When using a transductive link with pedagogical intent, we aim to construct a semiotic resource with high pedagogical affordance. This means that we must not only understand the physics the semiotic resource aims to showcase, but also understand how to present it in a pedagogical manner. Different transductive links may, and probably should, be used depending on if the outcome is intended for the discipline or for pedagogical purposes.

By using a laser-based measuring device to measure the distance between two objects instead of using an actual measuring tape may reduce the pedagogical aspects of the situation and increase the disciplinary aspects. It may not be important to get an exact measurement, but it may be important to gain a tactile feeling for what it means to measure and how to do it. Thus, a researcher may investigate what a semiotic system provides if it is used as a transductive link, how it may be used, and its potential effect on the semiotic material itself.

B. Scaffolding for instruction

It is important for teachers and instructors to be aware of the effect that the use of transductions might have in a learning situation. Often instructors need to perform transductions themselves in the classroom, but other times their students need to be able to perform transductions on their own. In such a scenario, one needs to consider the intent of the transduction itself—"What is the purpose of the transduction in this situation?", "What should the transduction filter and what should it highlight?" Once these questions have been answered, the teacher, or the student, needs to choose one, or several, appropriate transductive links that will help facilitate these aspects.

As an example of this, we would like to describe a hypothetical scenario where the instructor has chosen to use speech and gestures as their transductive links.

- **Lecturer:** *Here we evaluate the function at zero* [points at the graph at (0, 0)] *and gets the value 5.* [points at the graph at (0, 5) and draws a point]
  By doing this for all x values we get a line of dots which represents our function. [draws a line in the graph]

The intent of the situation is to showcase how to move between a function and a graph (a transduction from a function to a graph) rather than to use the graph itself to showcase qualitative aspects of the function. To highlight the relationship between the function and the graph, the instructor used gestures and speech as their transductive links. The transductive link is thus used to construct a semiotic resource with high pedagogical affordance. If the intent of the transduction was different, such as having a talk at a scientific conference, there would be no need to use the speech or gestures to support the transduction itself. The graph would probably have been created using a program with the intent to reproduce the function in an accurate manner. The lecturer in the situation above has chosen their transductive links so that they are scaffolding the construction of the new semiotic resource in a pedagogical way for their students. The choice of transductive links to use in an educational setting should, thus, match the intent of the transduction and the ability of the students.

1. Variation of transductive links

With the identification of different transductive links comes the possibilities of changing and modifying them and observing the results. An instructor may try out different transductive links, or add new links to their chain, to further filter or enhance different relevant aspects. They may remove a link that they do not think serves its purpose and replace it with another link. This allows the teacher to identify weak links and to vary their teaching. Figure 9 shows a link being replaced with another to change how the semiotic material flows from one semiotic resource to another.

2. Transductive links and the flow of semiotic material

Transduction is the reproduction of semiotic material in a new mode. In social semiotics, we say that the transduction constructs a new semiotic resource based on the semiotic material in the initial semiotic resource. Thus, we may describe the transduction process as filtering, enhancing different aspects of the semiotic material, but also as a flow of semiotic material from one semiotic resource to another. The transductive links used in the transduction process are thus used to facilitate this flow of semiotic material, how it changes, how it is modified and how it will be used when a transduction is made. Changing the transductive links will affect the flow of semiotic material and some transductive links may hinder or improve the flow. How the semiotic material changes will affect the resulting semiotic resource because the semiotic resource is just a way of conveying the

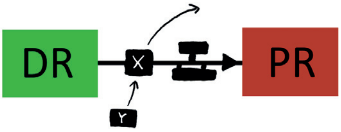

FIG. 9. A transductive link is changed or replaced to construct a new flow of semiotic material from the disciplinary resource (DR) to the pedagogical resource (PR). The new link will affect the transduction process and the affordances of the new semiotic resource.

semiotic material itself. In Fig. 9 we may think of the semiotic material flowing from the disciplinary resource to the pedagogical resource through the transductive link.

C. Identifying transductive links in literature

As we have described earlier, the concept of a transductive link has not previously been identified as a critical aspect in the learning process, nor has it been thought of in an analytic way in a PER perspective. By providing an in-depth discussion of transductive links, we offer researchers an opportunity to explore this new tool in their own research and to develop it further.

To exemplify how transductive links could be used analytically we have chosen four previously published physics education research articles as examples of how the concept of a transductive link could be employed as part of the analytical and descriptive process. In the first two examples [5,16], programming was identified as a transductive link when trying to learn physics and used as a transductive link between many different semiotic systems. Further, in these two articles, the authors analyse programming itself as a tool for enhancing the meaning making in physics education and identify different aspects of programming that could be useful when employed as a meaning-making tool. Such aspects were the ability of programming to act as a transductive link and the possibility of instant feedback to allow for an iterative approach to the exploratory process. These aspects of programming affect the transduction process when programming is used as a transductive link.

Our third chosen example comes from Ref. [3], who explored and described the role of transduction in science learning, specifically in the physics laboratory, through the use of digital or technical devices. The role of such devices in a physics laboratory (such as a telescope or a voltmeter) is described in terms of how they intensify and filter out different signals. In Fig. 3 in Ref. [3] they show an x-ray signal from outer space being detected by a satellite, and the satellite sending a processed version of the signal down to earth where a graph is produced. This process has filtered out unnecessary information and intensified the specific information that the signal contained, such as its direction, intensity, and wavelength. In this case, we argue that the satellite-earth-system performs the transduction in which mathematics and programming acts as the transductive links. Here, the programming allows the satellite to perform the necessary mathematical operations on the signal to filter out and to intensify the relevant semantic material while the system on earth interprets the signal and further transducts it into, say, a visible graph. Further, we believe that the concept of a transductive link could be used to describe other transductions that they describe throughout the article, but will provide just this single example for the sake of exemplifying the application of transductive links. Volkwyn *et al.* [3] ends the paper with a discussion about what makes different devices suitable to use for different content and concludes that different types of devices (that allows for transductions in different ways) are better suited for different circumstances. To us, this is an example of how different transductive links affect the possible meaning making in different ways.

Our fourth and final example of how transductive links can be identified from examples in the literature comes from Ref. [31]. In this example, Gregorcic, Planinsic, and Etkina [31] studied students' use of gestures when engaging with an interactive whiteboard through a physics playground program where they were asked to explore and discuss different physical concepts. Gregorcic *et al.* [31] give an example of a student who is using their hand to show how an object is moving in a circle around another object (the students in this situation are exploring Newton's law of gravitation and are observing different orbits). The student's use of gestures supports their speech as they attempt to move from a verbal description of the situation to a visual image. Thus, this is an example of where gestures are used as a transductive link while supporting the transduction.

Both Refs. [3,31] have rich descriptions of each particular learning situation and identify different aspects of them as having different roles. In these descriptions we find evidence of transductive links, as they are being defined in this paper, and would like to suggest that although the idea of transductive links may not be a new concept *per se*; it has been "hidden" in the research description. Thus, we propose that transductive links should be acknowledged as a concept for identifying and describing distinct parts of a learning situation, and have, through the above given examples, provided arguments for how transductive links may be used in the analytical process.

V. CONCLUSIONS

In this theoretical paper, we have used empirical work to define and explore the concept of a transductive link, as well as its role in a learning situation. We suggest that the concept of a transductive link should be considered an extension of the concept of transduction within social semiotics and multimodality. By providing multiple examples from PER, we show that it is useful for research in physics education. We believe that transductive links play an important role in students' learning processes and should therefore be identified as a potent analytic tool to be used when describing and understanding the learning challenges that students encounter in physics.

Different transductive links provide different opportunities for meaning making and the most appropriate transductive link to support the transduction process should be chosen depending on the learning goal of the situation. Further, two or more transductive links can be combined to create a transductive chain. The transductive chain is a natural expansion of transductive links and provides a mental image of how the semiotic material flows through different links before a final semiotic resource is obtained. Each link has its own weaknesses and strengths and affects the semiotic material differently. Transductive links and transductive chains thus allow for a novel description of different aspects of the learning process and the pertinent tools that are used in this process. By identifying the transductive links or chains in a given learning situation, we can begin to study how they affect the transduction process. Weak links may be identified and replaced by better links to improve the teaching and learning experience for the students.

We believe that further analysis of transductive links should aim at identifying how different links affect the transduction process and how the choices of transductive links affects the possibility for learning. This theoretical description of the learning situation will help us to identify and address weak links in students' meaning-making process and may help researchers and teachers to better understand the meaning-making process in physics at large.

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Paper IV

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Active and passive transductions—definitions and implications for learning

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Abstract
To move between different *semiotic systems*, such as graphs and formulas, is a necessary step in learning physics or solving problems. In *social semiotics*, this movement of *semiotic material* is called a *transduction* and during a transduction a student must *unpack*, *filter*, and *highlight* different aspects of the concept or problem. Unpacking, filtering, and highlighting have been shown to be important to the meaning-making process and transductions should be seen as indicators of meaning-making and learning. However, in this paper we argue that not all transductions performed by students requires unpacking, filtering, or highlighting, and hence the definition of transduction needs to be refined in its description. We introduce the ideas of *passive* and *active* transductions that separates transductions that may lead to meaning-making from transductions that may not. This separation is done through shown engagement with the semiotic material of the transduction. We connect shown engagement with the semiotic material to the already established *anatomy of disciplinary discernment* to create a useful tool when evaluating student engagement and discernment. In the paper, we showcase examples of passive and active transductions and provide a short description of how to identify them in different learning situations.

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Keywords: transduction, social semiotics, disciplinary discernment

(Some figures may appear in colour only in the online journal)

1. Introduction

This theoretical paper aims to advance the description of *transduction* as used in s*ocial semiotics* in physics educational practices and research. Since a full review of social semiotics and transductions is beyond the scope of this paper, we refer the reader to [1–3] for more detailed descriptions, and move straight to the details relevant for this paper.

The act of performing transductions [1–5] have been shown to play an important role in the meaning-making process and is defined by Jeff Bezemer (page 169) [6] as:

$$The\, movement\, of\, semiotic\, material\, from\, one\, mode\, to\, another,$$

where the concept of 'mode' has been substituted by *semiotic system* within the social semiotics framework. A semiotic system is a qualitatively different way of representing the *semiotic material*, for example, a formula or text used to represent the semiotic material of 'force'. In the transduction from text to formula, we lose the verbal description of the concept but gain the possibility to discern a symbolic relationship between the different parts. In equation (1) we perform a transduction between 'formula' and 'text' while attempting to preserve the semiotic material of 'force'.

$$\bar{F} = m\bar{a} \leftrightarrow \begin{cases} \text{Force is equal to mass times acceleration.} \\ \text{A heavy object experiences less} \\ \text{acceleration compared to a lighter object} \\ \text{when experiencing the same force.} \end{cases} \tag{1}$$

Another example of a typical transduction is the act of moving semiotic material from the semiotic system of 'text' to 'image', or some other visual semiotic system. In figure 1 we see an example of such a transduction. In the transduction, we see that a number of implicit questions has been answered, such as: what color is the ball? How large is it? By answering these questions, the person performing the transduction engages with the semiotic material of 'a ball' because they have to consider how to represent the semiotic material in a new semiotic system.

1.1. Transductions with engagement: unpacking, filtering, and highlighting

During the transduction process, many questions emerge that must be answered. This process involves *unpacking*, *filtering*, and *highlighting* different aspects [3]—What aspects do we keep, how do we represent them, what do we throw away? In equation (1), we must decide how to represent 'force' as a mathematical symbol, $\bar{F}$. Do we write the whole vector: $\bar{F} = (F_x, F_y, F_z)$ or do we forego the vector notation completely?

In [5, 7] Svensson *et al* uses programming to perform the transduction and shows how programming requires these steps when it is employed in a learning environment. Unpacking [8] has previously been shown to help students to discern disciplinary relevant aspects [9] from representations that may have been difficult to discern without discussions with peers or an instructor.

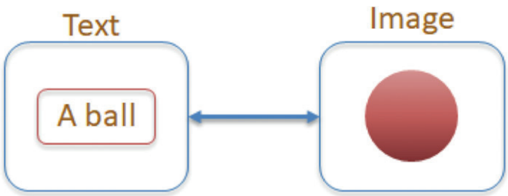

Figure 1. A transduction is performed between the semiotic systems 'text' and 'image'.

Using the previous research of Eriksson *et al* [10], we are able to connect transductions with the anatomy of disciplinary discernment (ADD), see figures 6 and 7. The connection between transductions and ADD provides us with a more detailed description of students' engagement and disciplinary discernment in the learning situation.

1.2. Transductions without engagement

The processes of unpacking, filtering, and highlighting different aspects, requires engagement with the semiotic material. The semiotic material must be studied and its parts must be understood and put back together in a new representation. However, in this paper we present transductions where students seemingly do *not* engage with the semiotic material, showcasing that a performed transduction does not necessarily mean that the student performs the unpacking, filtering, or highlighting steps. We therefore suggest a division of transductions into two classes: *active and passive transductions*. In the following sections we discuss how these can be defined and used to analyze and improve the learning situation.

2. Active and passive transductions

Below follows the definitions of the two types of transductions that we have identified:

Active transduction : *the student shows engagement with the semiotic material during the transduction.*

Passive transduction : *the student does not shows engagement with the semiotic material during the transduction.*

Where we view *engagement* as: *students play an active role in the unpacking, filtering, or highlighting of aspect in the transduction*, such as asking what $\bar{F}$ means to unpack it, or using different colors for different aspects in a function and its corresponding graph to highlight the connection between them.

A student does not engage with the semiotic material if no unpacking, filtering, or highlighting takes place. If a lecturer says:

'Write down 'F' equals 'm' 'a','

and the student writes it down, the student has not engaged with the semiotic material, but merely copied it over from one semiotic system–'speech'–to another–'formula'. Using the old definition [11], this is technically a transduction; however, we cannot couple it to any

Example 1: active transduction

1	**Fredrik**	We have the formula for heat. [Gustaf nods]. The ‘Q’ equals to, what is it, ‘$mc\Delta T$’?
2	**Gustaf**	yeah.
3	**Fredrik**	Should I write it down…I can write it down
4	**Kim**	Yes, please do. [Fredrik draws a ‘Q’]
5	**Fredrik**	we have ‘m’ ‘c’ ‘ΔT’ [Fredrik draws the symbols as he speaks]
6		[Fredrik writes ‘mass’ and draws an arrow from the word ‘mass’ to the ‘m’ in the formula.]
7	**Fredrik**	‘c’ is the…. [Draws an arrow pointing to ‘c’] what is this called?
8	**Gustaf**	Heat capacity…
9	**Fredrik**	It’s called heat capacity…specific heat capacity, yeah.
10		[Fredrik writes heat capacity at the arrow point to ‘c’]
11	**Fredrik**	And ‘ΔT’ is the, well, change in temperature.
12		[Fredrik draws an arrow pointing to ‘ΔT’]

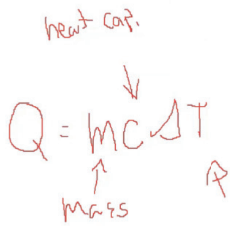

Figure 2. Fredrik writes down the formula for thermal energy, $Q = mC_v\Delta T$, but also modifies it by adding arrows and words to explain it. Fredrik unpacks the representation and highlights different aspects. This is an example of an active transduction performed by a student.

unpacking, filtering, or highlighting, nor can we say that the student discerns or explores any aspect during the transduction, which leads us to revise and refine the definition into the sub-definitions above.

The terms *passive* and *active* should not be interpreted as value-judgment of students individual learning situation, but only as neutral descriptive terms of the situation. Thus, a passive transduction should not be seen as a negative outcome of a learning situation, but as an indicator that this specific transduction does not provide any information for use in assessing the learning situation or outcome.

Example 2: passive transduction

1		[Fredrik is looking up the formula on a formula sheet]
2		[Fredrik begins to write down the formula $\Delta U = nC_v\Delta T$]
3	**Fredrik**	I am just copying the formula.
4		[Fredrik adds: $= f/2nR\Delta T$]
5	**Gustaf**	Yeah, sure
6		[Fredrik adds: $= f/2Nk\Delta T$]
7	**Kim**	And what does that formula say?

$$\Delta U = nC_v \Delta T = \frac{f}{2} nR\Delta T = \frac{f}{2} Nk \Delta T$$

Figure 3. Fredrik copies the formula, but without engaging the semiotic material. This is an example of a passive transduction.

2.1. Data collection

The four examples presented in this paper come from three different studies performed by the authors. Examples 1 and 2 come from the project '*constructing semiotic resources using social semiotics and variation theory for use in physics education*' that is lead by Kim Svensson of the LUPER group at Lund University. Examples 1, 2, and 3 are all from physics students discussing or solving physics problems. Example 3 is from Campos *et al* [12], where physics students explored and solved problems in relation to electromagnetic fields. Example 4 comes from a geoscience education research study by Lundqvist *et al* [13], where students are tasked with discussing and representing geological time.

2.2. Informed consent

The students in examples 1, 2, and 4 were all volunteers for the research and have signed consent forms that comply with the general data protection regulation (GDPR, Regulation (EU) 2016/679). The data collection for examples 1, 2, and 4 took place at Lund University in Sweden by authors Kim Svensson and Jennie Lundqvist, no ethics committee was required. All names in examples 1, 2, and 4, are fictitious and cannot be traced back to the students. The data collection for example 3 took place in Tecnologico de Monterrey in Mexico with volunteers who signed informed consent to participate in the research. All volunteers answered the questions anonymously.

2.3. Examples

Below follows a number of examples that have been chosen to showcase different active and passive transductions.

Example 3: passive transduction

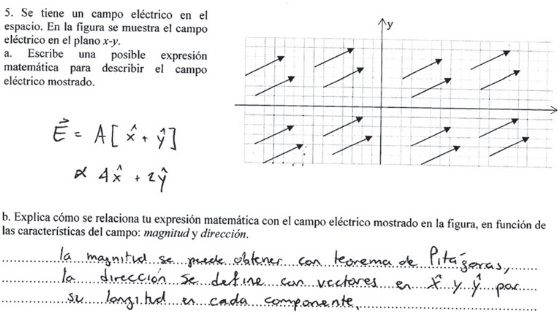

Figure 4. The task given to the students in Spanish.

Translated into English:
5. There is an electric field in space. The figure shows a part of the electric field in the x–y plane.
a. Write a possible mathematical expression to describe the electric field shown.
b. Explain how your mathematical expression relates to the electric field shown in the figure, in terms of the features of the field: magnitude and direction.

The student answered:

a.

$$\vec{E} = A[\hat{x} + \hat{y}]$$
$$\propto 4\hat{x} + 2\hat{y}$$

b. 'The magnitude can be obtained using the Pythagorean theorem, the direction is defined with vectors x and y and by the length of each component.'

In examples 1 and 2, the transductions are primarily performed by the student Fredrik in regards to an exercise about heat and thermal energy. In example 1, Fredrik performs an active transduction from 'speech' to 'formula' and during the transduction he adds arrows and words to unpack it, as seen above in the transcription and in figure 1. Fredrik engages with the semiotic material and makes choices during the transduction. He chooses what to unpack and what to highlight based on what he finds relevant to the situation. Kim, one of the authors of this paper, is the interviewer in examples 1 and 2.

However, in the transcript in example 2, the same student performs a passive transduction, where he does not engage with the semiotic material during the transduction process. It was

Example 4: active transduction

1	**Hutton**	It is quite simple, the paper we received in the beginning of [the first course]
2	**Interviewer**	How do you visualize it in your mind /.../ when you talk about geological time how does it look inside your mind?
3		/.../
4	**Lyell**	It is true that Silur and those in the beginning are blue /.../ we see yes, we see color, we see time as color.
5	**Agassiz**	You can, then, it's not something that is completely wrong
6	**Lyell**	Color
7	**Hutton**	I think there are three pieces of red
8		[Hutton is quiet for a while and is occupied with drawing figure 5, when the drawing is finished, he exclaims]
9	**Hutton**	This is what it looks like
10	**Interviewer**	Is this how you visualize it (points at figure 5)
11	**Hutton**	Yes, this is what it looks like in my room

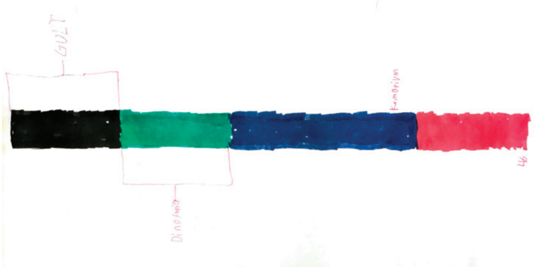

Figure 5. A linear representation of geological time in the form of a vertical column with sharp distinct borders between the colored fields that represents different parts of Earth's history. The representation has been rotated 90 degrees.

not until Fredrik or Gustaf were prompted, on line 7, to describe the formula that they began to engage with the semiotic material of the representation; a short moment after the transduction was complete. In figure 3 we see the result of the passive transduction.

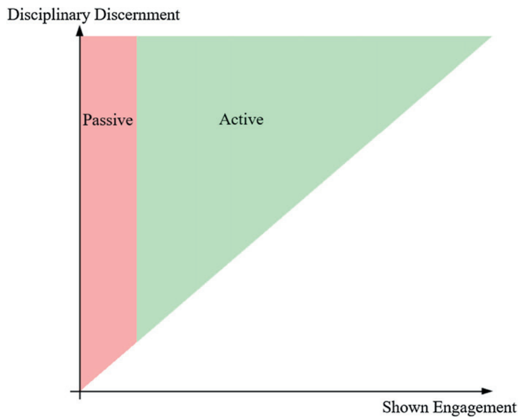

Figure 6. A student must be able to discern what the representation affords before the student may engage with the semiotic material. The larger the engagement is, the higher up the disciplinary discernment hierarchy the student must be. However, the reverse is not true, a student may display low engagement and high disciplinary discernment.

In example 4 we see an active transduction where Hutton engages with the semiotic material of geologic time. The data comes from semi-structured interview with first year geoscience students at a Swedish university [13].

In the excerpt above Hutton begin the active transduction by moving the initial mental image of geologic time into speech in line 2 and into a drawing in line 4. This is an example of an active transduction but with a low engagement. In the drawing we can see some attempts of unpacking through the notations of dinosaurs, Cambrian and the number 46 but there is no further explanation. When the drawing is finished there is no further interaction or exploration of the image but rather a finalizing statement that concludes that this is how it is.

2.4. Identifying passive and active transductions

As seen in example 3, it is not trivial to identify if a transduction is active or passive. The first step is to define what semiotic material is in focus in the transduction. In example 3, the semiotic material is the electric field, however, the transduction in example 3 may be performed with no shown engagement with the electric field at all, only with the vector field representation.

In example 1, Fredrik is actively showing how the mathematical formula is related to physical quantities such as mass, specific heat capacity and temperature. Fredrik thus engages with the semiotic material, by unpacking it, and performs an active transduction.

If a student engages with the intended semiotic material during the transduction, it is an active transduction, else it is a passive transduction.

2.5. Connection to disciplinary discernment

Eriksson *et al* 2014 [10] introduces the ADD and it provides a hierarchy of student discernment of disciplinary relevant aspects. Discernment is also identified as a necessary condition of learning [14] and we apply this notion to our active and passive transductions. We suggest that the shown engagement may be used to help determine the disciplinary discernment level, but we refer back to Eriksson *et al* 2014 for a deeper description of these levels and how to identify them. See figure 6 for a graphical representation of this. Figure 6 presents how passive and active transductions can relate with either low or high disciplinary discernment level. Also, the passive or active transductions can be seen as a continuum, where students can transition from passive to active transductions and vice versa, while increasing (or reducing) their disciplinary discernment level. The students disciplinary discernment level determines their potential for engagement with the semiotic material. Without any discernment, the student may not engage with the semiotic material at all.

3. Conclusion

A transduction does not necessarily mean that a student unpacks, filters, or highlights different aspects of the semiotic material. In situations, the process may be just more akin to copying, or writing things down that someone says, without any disciplinary reflection. In this paper we introduce two new categories of transductions: active and passive transductions that aims to separate the two cases. In the case of the active transduction, the student engages with the semiotic material and performs one or several of the actions: unpack, filter, or highlight on the semiotic material, hence show signs of learning, according to social semiotics. In the case of the passive transduction, the student writes down, or copies, what is presented to them (moves from one semiotic system to another) without any engagement with, or disciplinary reflection on, the semiotic material.

Other theories have also identified the distinction between active and passive transductions as important. For example, the theory of registers of semiotic representations identifies ‘transitional auxiliary representations’ as the changes of representations that do not imply cognitive activity [15]. We highlight that ‘conversions’ in the theory of registers of semiotic representations are directly related to active transductions, because they both imply cognitive activity, such as unpacking, filtering and highlighting. Whereas, ‘transitional auxiliary representations’ may be related to passive transductions, because students do not engage with the semiotic material, when the transitional auxiliary representations are used. In example 3, the student was able to move between different representation systems without recognizing the characteristics of the electric field, probably due to the fact that students are familiar with the conversions between vector diagrams and algebraic equations; in this way, the familiarity with the representation systems would act as the transitional auxiliary representation.

It is important to acknowledge the relevance of the context in which each theory developed. On the one hand, the theory of registers of semiotic representations comes from the didactics of mathematics and claims that cognitive activity in mathematics depends on the transformation of representations (treatments and conversions) [15]. In this context it is necessary to distinguish conversions as the changes of representation that denote cognitive activity, and transitional auxiliary representations as those that do not. On the other hand, social semiotics describes a wide range of processes that happen when learners engage with semiotic material in the physics education context. Therefore, transductions describe a wide range of processes, and it has become relevant to identify active and passive transductions in relation to disciplinary discernment and the processes of unpacking, filtering and highlighting.

4. Implications

Merely identifying that transductions, according to [11], are performed by the student is not enough to infer that they involve any unpacking, filtering, or highlighting parts of a transduction leading to meaning-making. To obtain a better description of the situation, a researcher must also identify if this transduction is active or passive.

From previous studies [16–18] we know that student engagement with the semiotic material is important for learning and practitioners should aim to create learning situations where active transductions are taking place instead of passive transductions. A practitioner should ask the question: 'are the students only writing down what I am saying, or are they engaging with the semiotic material?' and modify their teaching methods to avoid passive transductions taking place.

To avoid passive transductions, we suggest that practitioners adopt active learning [19, 20] techniques and employ the variation theory of learning [14, 21, 22] to ensure greater engagement with the semiotic material by the students.

4.1. Plotting the engagement

The examples presented in section 2.3 can be placed within the graph presented in figure 6. By plotting where the transductions are located in the 'disciplinary discernment' and 'representational engagement' plane we obtain a better view of how fluent the students are in their usage of representations. For example, if all transductions are in the upper right corner of the plot, the material may appear too easy for the students since they do not need to engage with the semiotic material at all when they are performing the transduction. However, if they are all in the bottom left corner, the material may be on a too high a level and the students can not engage with the semiotic material because they cannot discern what is important and what is not important. In figure 7 we see the examples plotted and identify areas of the plot that may be important for the planning and execution of the learning situation.

4.2. Designing assessments

In example 3, the student believes that they have done what is asked of them. However, if the exercise can be solved by the student without them showing any engagement with the semiotic material, the exercise is not a good way to assess student understanding of the physical concept. If the student solves the problem using passive transductions, we cannot say anything about their disciplinary discernment of the physical concept, as shown in figure 6.

It is important to identify exercises that may be solved using only passive transductions to acknowledge their limitations when designing assessments. Assessments should thus focus on making the student engage, and show this engagement, with the semiotic material to be useful during the assessment process. However, a student may still engage with the semiotic material when solving the exercise, but if they do not show it, we cannot say that they do, nor their level of understanding. As such, when assessing students, one must construct tasks and problems that allows for many transductions. See e.g., [23–25] for some activities that have shown potential of engaging students meaning-making. We also highlight the work by Trevor Volkwyn [3, 26, 27] on which the definitions of active and passive transductions are based, for a better understanding of how to induce transductions during the meaning-making process of students.

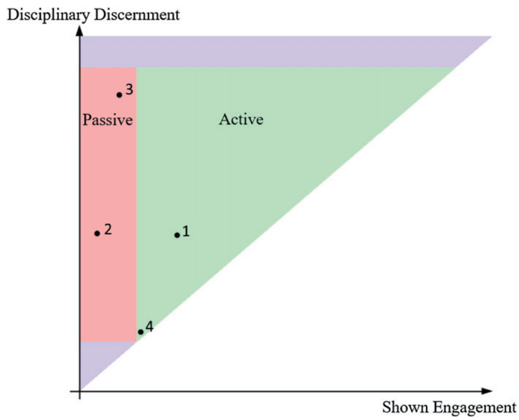

Figure 7. The examples (1–4) plotted in the diagram. The disciplinary discernment level has been estimated based on other interactions with the students in question. The top purple area indicates an area where the student is unable to progress and the bottom pink area indicates an area where the students are unable to engage with the semiotic material.

4.3. Interventions and passive transductions

In example 2, the student Fredrik performs a passive transduction and he, and Gustaf, only begins to engage with the semiotic material after they are prompted by Kim, the interviewer. The passive transduction provided an opening for a well timed intervention. Thus, teachers may use passive transductions as indicators that they may want to perform an intervention to get the students to engage with the semiotic material.

4.4. Future research

Future research that incorporates or expands upon the ideas presented in this paper could include looking at the construction of tasks and representations to allow for active transductions. This will be incorporated into an analysis done by one of the authors in an ongoing project where the data presented in examples 1 and 2 will be used.

Requiring students to perform active transductions on all tasks they perform may be taxing and mentally exhausting. A mix of passive and active transductions may be a desired were the active transductions are directed toward what a lecturer wants to assess, but that other transductions may be kept passive to not overwhelm the student. This could be connected to, and explored by, cognitive load theory as '…*extraneous cognitive load* […] *caused by task-related aspects*…' [28].

5. Summary

In this paper we have refined the definition of transductions in social semiotics to include passive and active transductions. Passive and active transductions capture the students' shown engagement with the semiotic material of the concept in question.

Active transductions signals that students are higher up in the disciplinary discernment hierarchy. Usually, the more the student engages with the semiotic material, the further up the hierarchy they are. Passive transductions signals that the student does not engage with the semiotic material. There are several reasons why a student may not engage with the semiotic material; they do not discern the semiotic material itself and cannot engage with it, or they have no need to engage with the semiotic material because it is second nature to them, or they are disinterested in the exercise, or they do not have to engage with the semiotic material to solve the problem.

A passive transduction provides no information about the students' disciplinary discernment. An assessment should be designed to encourage the student to perform active transductions so that their disciplinary discernment may be observed. By using interventions at opportune moments, students may be encouraged to turn a passive transduction into an active one.

We have applied the ideas of passive and active transductions to physics education research and geoscience education research. However, the ideas presented here and the concept of transduction can, and should, be applied to any type of educational setting where representations are used in the meaning-making process.

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Paper V

How do students use representations in physics? A comparison of two semiotic perspectives

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The study of students' use of representations is one of the main topics of Physics Education Research and is guided by the overarching field of semiotics. In this paper we compare two semiotic frameworks, one coming from didactics of mathematics and one from physics education research; *The Theory of Registers of Semiotic Representations* and *Social Semiotics*. A group of first year university students were audio and video recorded as they discussed concepts relating to thermal energy. We find that analyzing the recorded data using two different semiotic perspectives provides a wider interpretation of students' representational use, a descriptive approach to how students use the representations, and an approach to the cognitive aspects of the construction of knowledge. By comparing the theoretical constructs they employ, and how they are employed in the analysis process, we identify constructs that both frameworks have in common, but also where they differ. We have found that each semiotic theory provides a different perspective regarding students' representational use. We also propose that comparing different theories may provide a space for complementing the constructs of each theory and providing a bigger picture to understand students' representational use in physics and other STEM education areas.

Keywords: Physics Education Research, Semiotic Representations, Social Semiotics, Theory of Registers of Semiotic Representations, Theoretical Framework, Higher Education, STEM Education

I. INTRODUCTION

To explain and to understand learning we must construct theories with the aim to describe the learning process. These theories are called theoretical frameworks and in this paper we will compare two theoretical frameworks that are being used in educational research — *Social Semiotics* (SS) [1–3] and *The Theory of Registers of Semiotic Representations* (TRSR) [4–6] — by applying each framework to the analysis of the same empirical data. We will do so by first contrasting the theoretical constructs used in both theories, and second, by using the theories to analyze the same data set and comparing the results. This approach allows us to compare both the theoretical constructs with each other, but also how they are applied in practice. Both frameworks are used to describe meaning making or learning that occurs with the help of representations in either mathematics or physics and in this paper, we apply both of them in a physics education setting. The analysis builds upon, and extends, the analysis found in Ref. [7] who analyzed the same data using TRSR and the *Onto-semiotic Approach to Mathematical Cognition and Instruction* [8]. We expand the analysis by also comparing the theoretical constructs of each framework to provide a deeper understanding of similarities and differences between the two frameworks.

The aim of this paper is to highlight both similarities and differences between the two frameworks in order to identify possible ways that the frameworks can be expanded and/or be used in parallel to produce a richer understanding of different learning situations.

The qualitative data used for the analysis consisted of group interviews with university physics students in Sweden. During the interviews, which were held over Zoom™, the students discussed tasks around the concept of thermal energy and were encouraged to use the annotate feature of Zoom™ to construct their own representations, such as, text, diagrams, graphs, and equations.

The paper begins with a short description of the field of *Semiotics* on which both frameworks are built. Then follows a description of the two frameworks as well as of the method used for data collection and analysis. We then present the results as both a theoretical comparison of central concepts from the two frameworks as well as a comparison of the results from the analysis. We end the paper with a discussion of the usefulness of this type of theoretical comparison, both with respect to the richness of the description during the analysis, but also with respect to the further development of the theoretical frameworks.

II. SEMIOTICS

The theoretical starting point of both SS and TRSR is located within *semiotics*. Semiotics, which can be traced back to either de Saussure (e.g., [9]), or Peirce (e.g., [10]), deals with the interpretation of various signs, how these are constructed, what they mean, and what meaning may be extracted from them. The two frameworks described

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in this paper deal with the meaning making that occurs when students interact, manipulate, and communicate using different representations within a subject such as physics. Representations are established signs within the physics discipline and the manipulation and construction of these representations is seen as a necessary step towards becoming a physics expert [11]. A physics concept must be either experienced, or represented in some way, for a student to have the opportunity to discern and learn it. Each representation is designed to showcase some aspects of the concept, but one representation can not make all aspects of the concept visible to students. Thus, it is natural to apply the ideas of semiotics to explain how students use, construct, and communicate physics concepts using formulas, graphs, diagrams, and more. Any study of how students use and interpret formulas, for example, becomes a study of the semiotics of formula use.

A. Representational research in PER

Representations and student's usage of representations have been investigated within the physics education research field, as evident by the two theoretical frameworks compared in this paper. The type of representation that is used when presenting physics problems affects how well students perform on the problem [12]. Thus, the student's representational competence [13, 14] affects how well they can extract disciplinary knowledge and how they approach the situation. Thus, we may obtain insights into the student's understanding of the physics and their representational competency by studying how students use and construct disciplinary relevant representations. For example, Ref. [15] found that experts and novices use representations differently when solving physics-related problems. Both novices and experts use many different types of representations, but the experts solved the problem faster and moved easier between different representations compared to novices. Thus, how students use representations [16–18], move between them [19–22], and how they choose to construct them [23, 24], all provide insights into the student's understanding of the physics content of the situation the students are engaged with. Both social semiotics and the theory of registers of semiotic representations aim to describe how students use representations to learn, and communicate ideas within the physics discipline.

B. Social Semiotics (SS)

SS was initiated in 1978 by Halliday [1] as a description of language. It aimed to describe language's different parts from an interpretive and meaning-making perspective. The framework has evolved over the years and, in this paper, we will use SS as it is presented in [2] (with the additional theoretical developments of Refs. [25–27]). Airey & Linder [2] (p. 95) define SS as:

"the study of the development and reproduction of specialized systems of meaning making in particular sections of society"

and have applied SS to the study of learning physics [28–30].

Concepts within disciplines such as physics and mathematics must be represented in such a way that a learner may experience and explore them. The concept of 'Force' must be represented in a way that allows a learner to discern some distinct aspects of it, such as direction, magnitude, or contact point. These representations are often mathematical formulations, graphs, diagrams or pictures. A specific representation, such as $\bar{F} = m\bar{a}$, is called a *semiotic resource* and is situated within a *semiotic system*: 'Equations'. A semiotic system is a system to construct and to represent concepts and each semiotic system is qualitatively different when compared to other semiotic systems. 'Equations,' 'Graphs,' 'Gestures,' and 'Images' are all examples of semiotic systems, within the discipline of physics, that are used by experts to communicate in the discipline, but also to introduce concepts to novices. See Fig. 1 for a schematic picture of the relationship between semiotic system and semiotic resources. Semiotic resources are not only representations, but also activities, equipment, or anything that is used to interpret or present disciplinary information. For example; a particle accelerator is a semiotic resource because it is used to make meaning of specific aspects of sub-atomic physics, just as a velocity-time diagram is used to make meaning about the relation between time and velocity in a specific situation.

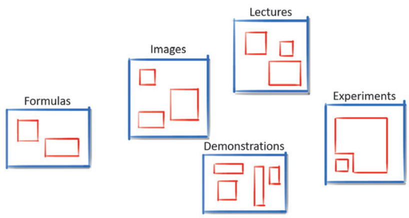

FIG. 1: Within each semiotic system, blue squares, exists many different semiotic resources, red squares.

SS draws on the Multimodality framework [3, 31–33] to describe how semiotic resources are used and transformed. If a semiotic resource is modified, but it stays within the same semiotic system, the modification is called a *transformation* but if the modification involves the movement between two different semiotic systems it is called a *transduction*.

For example, the modification of the formula $\bar{F} = m\bar{a}$ into $GMm\bar{r}/|\bar{r}|^3 = m\bar{a}$ is a transformation because it stays within the same semiotic system of 'Formula'. Whereas the modification shown in Fig. 2 is a transduction since it involves the movement between different semiotic systems.

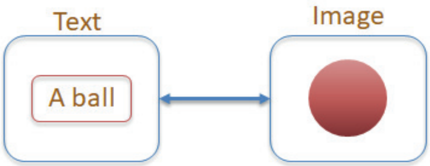

FIG. 2: A transduction is performed between the semiotic systems 'Text' and 'Image'.

1. *Understanding in Social Semiotics*

Any learning situation encompasses many transformations, transductions, semiotic resources, and semiotic systems to explore and experience the problem or concept at hand. In a learning environment we wish for students to obtain a *multifaceted way of knowing* [21] which means that a student has experienced, and discerned, a concept using many different semiotic systems and semiotic resources. A student should become fluent in using the semiotic resources and the movement between semiotic systems with regards to the specific concept, or *semiotic material*, in question. Semiotic material is the content that is represented in a representation, or the ideas that the representation aims to convey. In translations and transductions, we often wish to preserve or highlight some aspects of the semiotic material. A learning situation may be described in terms of changes to the discernibility of the semiotic material through the use of different semiotic resources and translations of the semiotic resources.

Within a semiotic resource, we may also investigate how well a student may discern important or disciplinary relevant aspects. Eriksson *et al* (2014) [34] constructed the *Anatomy of Disciplinary Discernment* that describes a hierarchy of discernment based on disciplinary knowledge. This hierarchy aims to capture all the ways to discern disciplinary relevant aspects from a disciplinary perspective and is tied to the students disciplinary understanding of the semiotic resource. The Anatomy of Disciplinary Discernment is described in detail in [34] and the levels are paraphrased here; from least discernment to most discernment:

- Disciplinary Identification: The student can name aspects of a representation using disciplinary specific terms.
- Disciplinary Explanation: The student can explain how aspects relate to each other in the representation, in a disciplinary way.
- Disciplinary Appreciation: The student appreciates the value of the representation with respect to its disciplinary content.
- Disciplinary Evaluation: The student can evaluate and find flaws in the representation from a disciplinary perspective.

C. Theory of Registers of Semiotic Representations

The theory of registers of semiotic representations was developed by Raymond Duval since the 1990's and early 2000's. Duval [4] considers that a representation is something that stands for something else, an object that can be tangible or intangible, such as ideas and concepts. A representation of an object can be physical when created by means of physical devices such as photographs, or semiotic when using symbols, rules and associations as tools to represent the object. In this theory, registers of representation are the semiotic representational systems that allow for transformation.

In natural sciences, such as physics, chemistry and biology, the objects of study are directly or indirectly approachable. This allows representing the objects with several semiotic and physical representations and relating the representations with the object. In contrast, mathematical objects of study are only accessible through semiotic representations [4]. Similarly, there are some highly abstract concepts in physics and other natural sciences that are only directly approachable with semiotic representations and indirectly with physical representations [6].

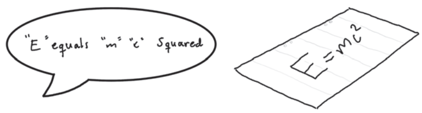

FIG. 3: Two semiotic representations of the same underlying mathematical object. Both semiotic representations are part of the same semiotic register: the algebraic register. On the left is the spoken form and on the right is the written form of the algebraic register.

The theory of registers of semiotic representations suggests that the cognitive activity in mathematics resides in the use of semiotic representations that allow the development of mathematical thought [4]. The use of semiotic representations for mathematical cognitive activity creates a paradox because, on the one hand, mathematical objects are only accessible through semiotic representations while; on the other hand, the mathematical object should not be confused with its representation. The challenge in the learning of mathematics and other abstract concepts is to dissociate the object from its representations, which can only be achieved through the use of multiple semiotic representations.

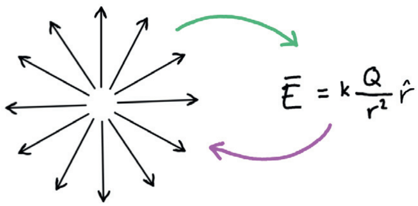

FIG. 4: A conversion between the graphical register and the algebraic register. The difficulty of performing a conversion has been shown to depend on the direction of the conversion. Here the conversion is between a field line representation of an electric field and the formulaic representation of the field. Students must recognize that both semiotic representations aim to represent the same mathematical object.

Using multiple semiotic representations requires that these representational systems can be transformed. However, not all representational systems can be transformed; then, only the representational systems that allow for transformation are considered registers of semiotic representation. Identifying the registers of semiotic representation that are involved in a cognitive process is the first part for analyzing students' understanding. To identify registers effectively, it is important to understand what is a register and how registers are transformed. In Fig. 3 we present an example of the algebraic register used to describe the physical concept of energy. The speech balloon on the left side represents the spoken form of the algebraic register, a person reciting the equation, while the right side represents the written form of the equation. Even though the delivery of the information is different (spoken and written), the semiotic content is the same, the algebraic relation between energy and mass.

Transformation can be treatments, which happen within the same semiotic register, and conversions, which happen between two or more registers that denote the same characteristics of the mathematical object. For example, the modification of the formula $\bar{E} = \bar{F}/q$ into $\bar{E} = kQ/r^2\hat{r}$ is a treatment because it stays within the algebraic register. Whereas the modification shown in Fig. 4 is a conversion since it involves the movement between different semiotic systems. Fig. 4 represents the conversion between the graphical register and the algebraic register. It shows the electric field lines and an algebraic representation of the same field; a student must recognize that the same mathematical object is represented in both registers. Conversions are more complex than treatments because they require the recognition of the same object in two semiotic systems that represent the same object with different characteristics. Duval identified that the recognition of the object in the characteristics of the representation is one of the main sources of difficulty, and that these difficulties depend on the direction of conversion.

By describing the learning situation using semiotic registers, representations, treatments and conversions, we can identify when students may run into difficulties and investigate them accordingly.

III. METHODOLOGY

In our comparison between the two frameworks we aim to describe both their underlying theoretical constructs but also showcase how they are applied in an analytical situation. In SEC. V we provide a list of theoretical constructs for both frameworks and how they line up with each other. Later in SEC. V we provide some results from the analysis of applying both frameworks on the same set of data.

A. Data Collection

To be able to perform a comparison on how the two theoretical frameworks are applied to analyze a learning situation, we gathered data where students used representations to discuss and explore the concept of thermal energy. The aim of the data collection was not to investigate the students' understanding, but to capture data that has a wide range of usages of representations by the students. It's important to note at this point that the connection between representational use and understanding is made through the analysis of such data within each of the theoretical frameworks.

1. Participants

The participants that took part were first year university physics students and first year physics teacher students at a well known university in Sweden. The participation was voluntary and the participants were recruited through a physics course during their first year. All participants signed a consent that complied with The General Data Protection Regulation (GDPR, Regulation (EU) 2016/679).

2. *Digital group interviews*

The interviews were done with two or three students at a time over Zoom™. During the interview, the students were encouraged to discuss the task at hand, but also to explore tangents where they produced or used different representations. Using the Zoom™ annotate function, the students could draw, point and write directly on the PowerPoint where the tasks were presented, see Fig. 5 for an example of this.

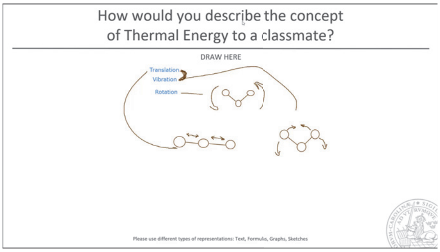

FIG. 5: Students discuss and solve the task together using the Zoom™ annotate function where they can draw and write using different shapes and colors. In the above example, two students discussed "How would you describe the concept of Thermal Energy to a classmate?" and drew representations of molecules in motion.

The PowerPoint presentation, the students faces and discussions, and the dynamic annotations were all recorded using the Zoom™ record function. Excerpts of the data is presented in the transcripts (Tables I, II, III, IV), together with a figure to provide context to the discussion if necessary.

B. Data selection

Not all the data, nor all results of the analysis, will be presented in this paper because this paper's focus is on the comparison between the two theoretical frameworks. A small subset of the data will be presented and analyzed by both frameworks so that a comparison can be made. A full analysis of the collected data will be presented in another paper that focuses on the construction of representations using social semiotics as a lens.

The selected data is chosen to showcase how the frameworks describe different representational manipulations and how these are related to the meaning-making process.

C. Quality Assurance

In this section we wish to address the steps we have taken to ensure that the research presented here is of high quality. We draw upon the categories described in Guba and Lincoln (1985) [35] as a first check.

a. Credibility The category aims to ensure that the findings are credible from the participants' point of view. We have achieved this by, during the interviews, allowing the participants to speak freely about the study and the questions and if there were aspects they felt that we missed. They were also encouraged, both in written and spoken form, to contact us if they wished to add anything to the data. The data itself is also processed as a whole, although, we do not present all the data in this paper, all the data was transcribed and analyzed.

b. Dependability The category aims to ensure that the study is repeatable if done with the same cohort, context, and researchers. This was achieved by keeping track of the study methods and by carefully designing the PowerPoint itself. The intent of the questions and what each slide in the PowerPoint is aimed to capture is documented and constructed with outside expertise. The analysis process employs established theoretical constructs from both frameworks with predefined definitions. Which reduces the mislabeling of aspects, ensuring that the same events would receive the same treatment if the study was repeated.

c. Confirmability The category aims to ensure that the study can be corroborated, or confirmed, by outside researchers. As the aim of this particular paper is to compare two theoretical frameworks, and not the particulars of the data from the data collection, we do no expect the data collection to be replicable with the information presented here. However, we expect that other researchers will come to the same conclusions if they apply both theoretical frameworks to their own data with the intent to compare them.

d. Transferability The category aims to ensure that the study can be generalized or transferred to other contexts. As the study's focus is on the comparison between theoretical frameworks, we expect that the methodology can be transferred to any data set where students are using representations to learn. However, this study was explicitly designed to capture students' usage of representations and other data sets may have been captured with other focuses. The application of the frameworks used in this paper may not be suited for a data set captured to study, for example, student attitudes or motivations.

IV. ANALYSIS

Below follows some example analyses when Social Semiotics and the Theory of Registers of Semiotic Representations are applied to describe a learning scenario where students solve and discuss physics concepts. In the transcripts, the formulas the students say out loud have been transcribed into formulas to be easier to read. We study how the use of multiple representations is related to understanding, by analyzing the data of using multiple representations with different theoretical frameworks. Each framework has its own way of describing understanding. In SS, we relate representational use with disciplinary discernment, while in TRSR, we relate it to recognition and dissociation.

A. Analysis using Social Semiotics

Social semiotics looks at the actions the students perform with respect to the representations. Such as, how they choose to construct them, what they deem necessary and relevant, and how they manipulate the representations to highlight important aspects.

1. *Identifying Transductions*

In the following transcript, Fredrik, with the help of Gustaf, performs a transduction between the semiotic systems 'Speech' and 'Formula'. We can see that Fredrik unpacks [28] the semiotic resource when he adds arrows and words to what the formula represents. The transduction results in the semiotic resource we see in Fig. 6, which is an unpacked version of the formula Fredrik and Gustaf spoke about.

TABLE I: Transcript of a transduction from speech to formula of the semiotic material of thermal energy

1	**Fredrik**	We have the formula for heat. [Gustaf nods].. The 'Q' equals to, what is it, 'mc Δ T'?
2	**Gustaf**	Yeah.
3	**Fredrik**	Should I write it down... I can write it down
4	**Kim**	Yes, please do. [Fredrik draws a 'Q']
5	**Fredrik**	We have 'm' 'c' 'Δ T' [Fredrik draws the symbols as he speaks]
6		[Fredrik writes 'mass' and draws an arrow from the word 'mass' to the 'm' in the formula.]
7	**Fredrik**	'c' is the.... [Draws and arrow pointing at 'c'] what is this called?
8	**Gustaf**	Heat Capacity...
9	**Fredrik**	It's called Heat Capacity... Specific Heat Capacity, yeah.
10		[Fredrik writes 'Heat Cap' at the arrow pointing at 'c']
11	**Fredrik**	And 'Δ T' is the, well, change in temperature.
12		[Fredrik draws an arrow pointing at 'Δ T']

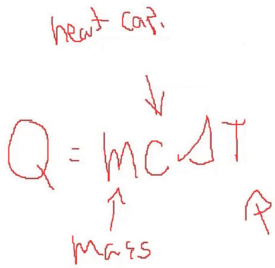

FIG. 6: Fredrik writes down the formula for thermal energy, $Q = mC_v\Delta T$, but also modifies it by adding arrows and words to explain it. Fredrik unpacks the representation and highlights different aspects, so that it will be easier to discern the meaning of the formula.

In Fig. 6, we have used the concept of transduction from social semiotics to describe the specific aspect of the meaning-making process. As part of the transduction process, we see that Fredrik unpacks the new semiotic resource to highlight different aspects. The aspects the Fredrik highlights are aspect that he has deemed relevant for the situation, either to understand it himself, or to communicate the meaning to the others. Unpacking, filtering, and highlighting has been identified as important parts of the transduction process [20, 36, 37]. In Ref. [22] Svensson *et al* introduces the distinction of *Passive* and *Active* Transductions and define them as follows:

Active Transduction: *The student shows engagement with the semiotic material during the transduction.*

Passive Transduction: *The student does not show engagement with the semiotic material during the transduction.*

In Table I we see that Fredrik engages with the semiotic material and we further identify the transduction as an active one.

2. *Identifying transformation*

In Table II, Fredrik performs a transformation of the formula as it is rewritten into different configurations. Transformations stay within the same semiotic system, in this case; the semiotic system 'Formula', and describes manipulations and rewrites of semiotic resources. In the transcript, Fredrik performs a translation when he rewrites $\Delta U = nC_v\Delta T$ as $f/2nR\Delta T$ and once more when it is written as $f/2Nk\Delta T$. However, we can not say that Fredrik or Gustaf engages with the semiotic material of the formula.

TABLE II: Transcript of a transformation of a formula

1		[Fredrik is looking up the formula on a formula sheet]
2		[Fredrik begins to write down the formula $\Delta U = nC_v\Delta T$]
3	**Fredrik**	I am just copying the formula.
4		[Fredrik adds: $= f/2nR\Delta T$]
5	**Gustaf**	Yeah, sure
6		[Fredrik adds: $= f/2Nk\Delta T$]
7	**Kim**	And what does that formula say?

$$\Delta U = nC_v\Delta T = \frac{f}{2} nR\Delta T = \frac{f}{2} Nk\,\Delta T$$

FIG. 7: Fredrik copies the formula, but without engaging the semiotic material.

In Fig. 7 we see the sequence of expressions that Fredrik wrote down. The act of writing it down sets the stage for new types of manipulations and discussions. In line 7 of the transcript in Table II we see the interviewer ask for an explanation of the formula. If the formula had not been written down, the interviewer would not be able to direct the conversation in new directions. Thus, even if the actual transformation was passive, it set the stage for interventions and new translations to be performed by the students.

3. *Semiotic Resources and DRAs*

In transcript I, we see that the students use specific words (spoken and written) and formulas to describe 'Heat' in this case. These are the semiotic resources they employ to communicate their knowledge to their peers. The semiotic resources are chosen because they provide access to the Disciplinary Relevant Aspects (DRA)[38, 39] of the situation. The DRAs are aspects that the discipline has deemed relevant for the situation, such as 'mass', 'specific heat capacity', 'temperature' and the relationship between them. The semiotic resources are established within the physics discipline and provides a common language for the students to use when exploring the concept. In Fig. 6 we see that Fredrik has identified some of DRAs of the situation and is providing opportunity for Gustaf and Hela to discern them as well by unpacking the formula.

4. *Disciplinary Discernment*

In Table I we see that the students engage with the semiotic material of the representation and Fredrik highlights different aspects of the concept by writing words and drawing arrows (lines 6, 7, 10, and 12). From this, we can say that Fredrik has, at least, reached the '*Disciplinary Explanation*' level of the Disciplinary Discernment hierarchy.

TABLE III: Transcript 3

1	**Fredrik**	So it would try to reach equilibrium which would mean that the gold would lose heat.
2	**Kim**	So what would happen to the representation in that case?
3	**Fredrik**	The volume would decrease.
4	**Hela**	In that case...
5	**Fredrik**	Well
6	**Hela**	where you say that... it's warmer than the room you put it in, the change in temperature is relative ... to the environment... and.. wait I just lost my train of thought for a second.... Right, yeah, if you define the zero-point as the environment then it would be the opposite of what we said earlier.

In Table III, we see that Hela comes to the realization that the interpretation of the representation is not unique and that it produces valid, correct results if interpreted in another way. We interpret this as Hela reaching the '*Disciplinary Appreciation*' level of the Disciplinary Discernment hierarchy because she acknowledges that the representation can be engaged with in different ways and that those ways of engaging with the representation are also valid.

B. Analysis using Registers of Semiotic Representation

In this section, we analyze the same example from the theory of registers of semiotic representations perspective.

1. Identification of registers of semiotic representations

We start this analysis by defining the registers that the participants Gustaf and Fredrik used: the algebraic and verbal registers. The algebraic register includes letters, numbers and symbols to represent a mathematical relation between physical quantities, such as heat, mass and the change of temperature. The verbal register uses words and sentences to represent the definitions of the physical quantities.

The episode in Table I presents how both registers appeared in the written and oral form in this example. In line 1, Fredrik recites the formula for heat, saying: "Cue equals to, what is it, em, cee, delta tee". This is an example of the algebraic register in the oral form, notice how Fredrik says the names of the consonants (Q=cue, m=em, c=cee, delta=Δ, and T=tee) to represent the physical quantities involved, and the name of the symbol =, equals to, to represent the relation between them. In line 5, Fredrik writes down the formula as he speaks, which is an example of the algebraic register in the written form. In lines 8 and 9, we see an example of the verbal register in oral form, when Gustaf and Fredrik assign the definition of heat capacity to the letter c in the equation. In line 10, Fredrik writes 'Heat capacity', which is an example of the verbal register in its written form.

2. Identification of conversions between registers of representation

Having identified the registers that are used, we look into the transformations that take place in this example. In Table I, we see that from lines 1 to 5, Fredrik and Gustaf are using the algebraic register in the written and oral forms. We might confuse the algebraic register in its oral form with the verbal register, but it is important to remember that the oral form of the algebraic register follows the symbols and associations of algebra, instead of assigning meaning through verbal representation. The participants start to assign meaning to the algebraic representation with the verbal register as followed. In line 6, Fredrik writes the word 'mass' and uses an arrow to relate the word 'mass' with the letter 'm' in the equation. This action indicates a change of register, from the algebraic register in its written form, to the verbal register in its written form. In this situation, the arrow acts as a transitional auxiliary representation to denote the conversion between registers (as seen in Fig. 6). From lines 6 to 12, we witness a series of conversions from the algebraic to the verbal register, both in written and oral forms. The students start assigning meaning to the algebraic register using the verbal register, this is the cognitive activity that underlies these conversions.

The example presented in Table II cannot be analyzed with the theory of registers of semiotic representations by itself, because precisely in this moment the students do not present cognitive activity by using the representation (Fredrik explicitly states 'I am just copying the formula'). However, it is interesting to analyze what happened right before and immediately after this example.

Right before the transcript in Table II, the participants had the conversation presented in Table IV. In line 1, Kim prompts the students to think of other representations for thermal energy, to which Gustaf responds with a verbal description and connects the concept with kinetic energy. In line 3, Kim asks the participants to draw this concept in some way, prompting for a conversion between the verbal description and a pictorial representation, a sketch. In lines 4 to 10, Hela makes this conversion between the verbal and pictorial register, since she explains how her sketch connects to the concept as she draws.

In line 11, Kim asks the participants to relate this sketch with a formula, to which Hela identifies there is a formula that relates temperature and kinetic energy. Then, the transcript in Table II takes place. Within this context, we can see that, even though the participants copy the formula from the textbook, they identified that there is a relation between this formula and Hela's sketch and verbal description. In this scenario, there is a conversion between three registers of representation: verbal, pictorial and algebraic registers. According to Duval, the cognitive activity requires the conversion between at least two or more registers [4].

TABLE IV: Transcript of a conversion between verbal register and a sketch

1	**Kim**	Do you have any other way of representing thermal energy, except for this equation or formula?
2	**Gustaf**	I think that vibration of the inner molecules is a good way of explaining it as well. Kinetic, as we were saying first, the kinetic energy.
3	**Kim**	Can you draw it in some way?
4	**Hela**	I can try.
5		[Hela begins drawing a blue rectangle to represent a container]
6	**Hela**	I mean, if we have some container... That isn't a very straight line... and some molecules...
7		[Hela Draws some smaller shapes in the container, representing molecules. Hela adds more molecules to the container].
8	**Hela**	Then I guess I can try to show that they move back and forth.
9		[Hela adds 'action lines' to some molecules]
10	**Hela**	At least if it is... more solid
11	**Kim**	Another question I have:... What is the relationship between the box with the molecules and the formula?
12	**Hela**	I think, if you wanted to connect them, you'd have to take an extra step and use... I think we have a formula as well, for temperature in terms of kinetic energy.

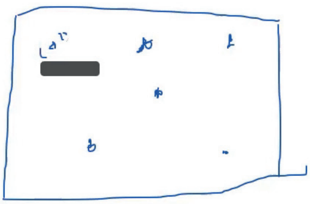

FIG. 8: Hela's sketch as constructed in Table IV. Hela has just added 'action lines' to the molecule on the top left corner; line 9 in the transcript.

Now let us see what happened immediately after Kim prompted the participants to think of a definition in Line 7 of Table II. An excerpt of the conversation that followed is in Table V. As we can see, Fredrik and Gustaf started converting from the algebraic to the verbal register by assigning a physical meaning to the elements of the equation, identifying whether they were variable or constant and what they meant. During this conversation, they not only assigned a meaning to the letter 'f' in the algebraic register, they went on to 'n' and 'N' in Fig. 7. The rest of this conversation is omitted for its length.

It is really interesting to see how the social interaction between peers allowed them to create conversions together. In the TRSR, the analysis of treatments and conversions is usually done in the individual level, because it refers directly to cognitive activity. However, using it in a social interaction has allowed us to encounter an example where conversions can happen socially. This is an area of opportunity where social semiotics and the TRSR can complement each other to provide a bigger picture.

TABLE V: Transcript of a conversion between peers

1	**Kim**	And what does that formula say?
2	**Fredrik**	Well, it is the formula for internal energy... for an ideal gas
3	**Gustaf**	Well, it's change in internal energy right
4	**Fredrik**	Yeah, and we have a couple of constants...
5	**Gustaf**	Is the 'f' also a constant? or what is the 'f'?
6	**Fredrik**	That would be the frequency of the vibration
7	**Gustaf**	Right, yeah

It is relevant to acknowledge that, in these examples, the cognitive activity was somehow prompted by the interviewer, which led to the conversions exemplified. This shows how with the right guidance and prompts, students can start engaging with the material and having cognitive activity through conversions. Moreover, the guidance and prompts can take place in a social environment, allowing instructors to include conversion in their active and collaborative learning design.

V. RESULTS

Here we present the results from the theoretical comparison of the two frameworks and the application of both theories. We also provide a result that emerged from the comparison of the framework; the development and construction of new theoretical constructs within the frameworks.

A. Comparing the frameworks

Representation systems are central parts of both theories. However, given that the TRSR is focused on the cognitive activity in Mathematics, the main tenet is that we can only access mathematical objects through semiotic representations. While in SS, the semiotic material can also be discerned with physical devices, such as photographs or measurement data. Therefore, using the TRSR to analyze students' representational use while learning physics is limited to highly abstract physics concepts (such as the electric field [6]), while SS allows for a broad range of physics concepts. Also due to the different nature of each theory, the TRSR allows linking the students' ability using several representation registers with their understanding of a concept, while SS focuses on disciplinary discernment. As we can see, both theories have their strengths and limitations, which will be analyzed with more detail throughout this section.

We have summarized the comparison in Fig. 9.

1. *Similarities*

Both SS and the TRSR describe representations used by students to learn. Both frameworks also identify changes to the representations as important aspects in the learning process. In Table VI we connect concepts in the two theories with each other. However redundant it may be, the first comparable aspects are the representamen and the semiotic object in each theory: in SS the semiotic object is the semiotic material and the representamen is the semiotic resources; in the TRSR, the semiotic objects are mathematical objects, and the representamen are registers of semiotic representation. In Table VI we also include the physical representations, but Duval explicitly states that the case of mathematical objects does not allow for physical representations [4].

Another aspect where we can find similarities is the structure with which both theories describe the changes of representation: whether they happen within one representation system, or if they involve more than one. The TRSR considers that cognitive activity in Mathematics happens through the transformation of registers of representation. In this theory, transformations can be treatments, when the transformation occurs in the same register, and conversions, when two or more registers are transformed. Similarly, in the SS theory, translations can be transformations when they happen in one semiotic system, and transduction, when two or more semiotic systems are involved. Within the transductions in SS, we identify active and passive transductions; active transductions can be compared to conversions with recognition in the TRSR [22], while passive transductions are comparable to conversions without recognition in the TRSR. This implies that recognition is a cognitive aspect in the TRSR.

Finally, the cognitive aspects have some similarities in both theories. We attempt to compare disciplinary discernment in SS with the cognitive activity in the TRSR, specifically with recognition and dissociation. These two cognitive aspects in the TRSR are identified as sources of difficulty in the learning of mathematics. Pertaining to understanding, SS describes students' multifaceted way of knowing when they can refer to several semiotic resources, while the TRSR describes mathematical comprehension when there is synergy between representations: students recognize the mathematical object in several registers, convert between them and dissociate the object from the representation.

As a big picture (see Fig. 9), this comparison proves that the two theories are sufficiently similar in their structure. However, while analyzing several examples, we found that the theories have subtle differences. This finding is important because the two theories are similar enough to allow for integration of knowledge, but different enough to provide contrasting lenses to tackle the research objectives with different angles, which may lead to enriched insight. We describe some of the differences in the subsequent section.

2. *Differences*

The most relevant difference between the two theoretical approaches is that the TRSR is limited to the cognitive activity around mathematical objects, while SS has a broader application to physics and science. This is a big difference because from there, all other differences emerge. The TRSR is focused on how transformations of representation define the cognitive activity in mathematics because there is no other way around. But in physics, we have other ways (like obtaining data) so the SS refers to HOW the representations are used, and it doesn't focus solely on cognitive activity. Since TRSR is limited to mathematical objects and other highly abstract concepts, the link between representational use and understanding is inevitable, while SS allows for more scientific and physical concepts even if it isn't too focused on understanding. This is where the two theories can interact and learn from each other.

A big difference between the two frameworks relates to the underlying division of representations. In SS, representations are divided into semiotic systems which groups representations in terms of HOW concepts are represented. For example, a written formula and a spoken formula are divided into 'Formula' (written) and 'Speech' (spoken). In the TRSR, the registers are not defined in the way they represent a concept, but by the content of the representation. Thus, a written formula and a spoken formula would be part of the same register: the algebraic register. However, the algebraic register takes on the written or oral form.

Derived from the previous differences, the relation between representational use and student understanding becomes critical. As emphasized before, SS refers to how students use representations in physics and other scientific contexts. When describing the how, SS classifies the representational abilities of students in the Anatomy of Disciplinary Discernment. This structure provides insight into whether students are able to identify, explain, appreciate and evaluate the disciplinary conditions of the representations that they are using. In the case of the TRSR, the relation between representational use and understanding is given through the synergy between representations. In this theory, the registers and their trans-

TABLE VI: Similarities between Social Semiotics and the Theory of Registers of Semiotic Representations

Aspect	Social Semiotics	Theory of Registers of Semiotic Representations
Semiotic object	Semiotic Material	Mathematical Object
Representamen	Semiotic Resources	Semiotic and Physical Representations
Representation change	Translation	Transformation
Changes within one system	Transformation	Treatments
Involving one or more systems	Active Transduction	Conversion with Recognition
	Passive Transduction	Conversion without Recognition
	Transductive Link	Transitional auxiliary representations
Cognitive aspects	Disciplinary Discernment	Recognition + Dissociation
Understanding	Multifaceted Way of Knowing	Mathematical Comprehension

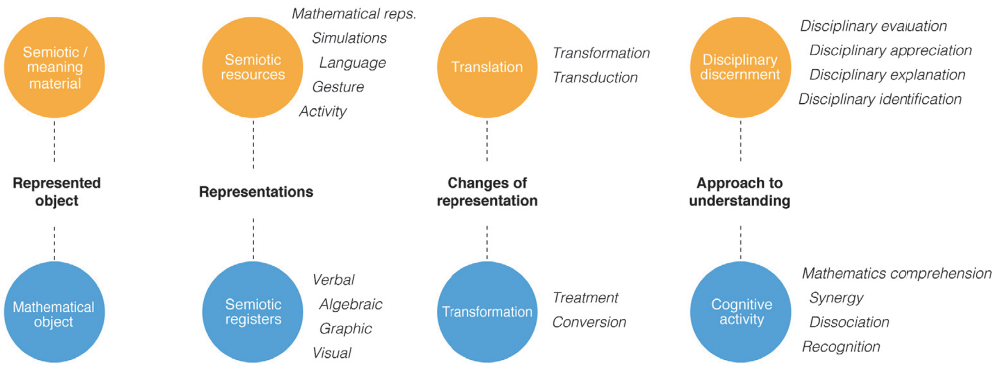

FIG. 9: Different areas that could be analyzed. With Social Semiotics approach on the yellow side and The theory of representations of semiotic registers on the blue side. Image created by Dr. Elias Euler for this paper.

formations are defined with the tenet of cognitive activity. The terms that describe the cognitive activity are the recognition of characteristics of the concept and the representation, and the dissociation between the concept and its representations. So, recognition and dissociation play an essential role in the cognitive activity, and they are part of the treatment and conversion of registers. In TRSR, representational use and understanding are directly linked, while SS creates this link indirectly, through the description of disciplinary discernment. The two theories together provide a broader picture where we can analyze the disciplinary discernment of students based on their representational use, as well as their understanding of the physical phenomena.

B. Analytical comparison

From Section IV, we can see that both theories aim to identify how the students manipulate different representations of thermal energy and how they move between the different representations. In Table I, in combination with Fig. 6, we see a movement from 'Speech' to 'Formula' and Fredrik is engaging with the physical concepts of the exercise. In SS, we identified this movement as an Active Transduction and in TRSR we identify it as a Conversion with Recognition.

1. Results from the Social Semiotics analysis

SS provided us with a language to describe the students' manipulations of the different representations they interacted with, such as the transduction we see in Table I together with Fig. 6. From previous work (e.g., [20, 26]) we know that transductions may help with the discernment of aspects. In Table III we have applied the ideas of Disciplinary Discernment to describe Hela's discernment of the representation and its uses from a disciplinary perspective.

By describing the learning situation in terms of transformations, transductions and disciplinary discernment levels, we gain a rich understanding of the learning situation. From the descriptions, we can identify what translations prompted student's to discern something in a new way and use this information to better understand the social construction of meaning and the potential problems that comes with learning physics. Using the knowledge of *what* translations afford, such as unpacking and highlighting aspects, interventions can be deployed that force students to grapple with specific aspects that they were unaware of or may find difficult. The intervention on line 7 in Table II is an example of applying this knowledge to make students grapple with the content of the formula.

2. Results from the Semiotic Registers analysis

The analysis using the TRSR yielded some interesting results. For instance, we found an example where we had both the verbal and algebraic register in their written and oral forms. This allowed us to identify clearly the characteristics of the algebraic and the written registers and how they are used by students in their cognitive activity. We identified that, when converting between the algebraic and the verbal registers, students assign meaning to the algebraic register by using the verbal register. This is evidence of cognitive activity, and of the relevance of the interaction of the verbal register with other representations [40, 41].

We later found that one student presented a conversion between three registers of representation, showing synergy between the representations. To have synergy between the registers implies that students can dissociate the concept from the representation, and recognize the characteristics of the concept in several representations. This is evidence of understanding in the light of the TRSR. A new finding within this theory was to see conversions happening as social interactions between peers, and also when being prompted by an instructor.

C. Developing the frameworks

An unforeseen, but welcome, effect of this study was the publication of Ref. [22]. In which SS are expanded to better describe transductions. In TRSR, conversions are separated into: conversions with recognition and; conversions without recognition. This was not the case in social semiotics, and the authors realized that it was an important distinction and introduced the notion of *Active* and *Passive* transductions.

VI. DISCUSSION

From the outset, we observed that the two theoretical frameworks could be closely related due to the fact that both frameworks appeared to have constructed similar theoretical constructs to explain similar phenomena in the learning space. For example, both frameworks identified the movement from formula to graph to be of importance for the learning process. The ideas of Transduction, from SS, and Conversion, from TRSR, are very similar and is an indication that this specific aspect of the learning situation is important.

Based on the analysis shown in this paper, we can conclude that the main difference between the frameworks comes from the lens they apply to describing the different theoretical constructs in each theory. SS applies a lens that aims to understand how communication and meaning-making is made in specialized groups, using specially constructed semiotic resources. Thus, SS describes how these semiotic resources are used and what they afford in the physics discipline, and avoids describing what happens inside a person's head.

TRSR uses a lens of cognition in its analysis and ties the manipulation of representations to the understanding of different concepts. This is one of the differences of the two frameworks. However, when the frameworks are used to analyze data, the identification of different specific uses or manipulations of different representations looks almost the same, they use different words and slightly different division of concepts.

Another difference is the notion of single student versus groups of students. SS is, as its name suggests, a framework to describe the meaning-making and communication in specialized groups. In SS, the notion of communication and the interaction between students becomes a central part of the analysis. However, TRSR is focused on single student's manipulation of representations.

The third big difference is TRSR's focus on mathematical objects with no physical representation such as imaginary numbers. TRSR makes a distinction between representations of physical objects and ideas that can only be manifested through representations. With SS we can study the concept of friction using different types of semiotic resources, such as; push a block on a bench; free-body diagrams; formulas, but TRSR is only designed to study mathematical concepts with no physical representation.

A. Using both frameworks

Based on our analysis in this paper, we find that both theories can be used in parallel to describe learning situations where representations are used, such as in physics or mathematics. We may incorporate the social aspect of SS to study how TRSR describes the manipulation of representations in groups, such as the conversion that was prompted by the interviewer in Table V. We may also apply the directionality of conversions from TRSR to the idea of transductions in SS to get a better understanding of the process itself. In an analytical sense, we do not see any problem to extracting useful concepts from one theory and applying them to the other. We suggest that researchers do this in order to obtain a richer description of the learning situation.

B. Caveat

The analysis here is just a first attempt at this type of comparison and there could be some further development of each framework that makes them incompatible in the future. However, we believe that any further development will bring them closer together and that the conclusions and implications from this paper will be even stronger.

SS is also used together with Variation Theory of Learning (VTL) [27, 42–44] to analyze the learning situation. VTL provides a framework to deal with the recognizing and separating a concept from its representation and is related to the ADD. VTL provides a mechanistic description of the process of discernment and ADD provides a way to describe types of discernment.

VII. IMPLICATIONS

Both theories have very similar theoretical constructs that describe the same aspect of the learning situation. Based on this, it should be possible to make valid comparisons between studies performed using SS and TRSR, as long as you take care to account for the different lenses the theories use.

Based on the work done in this project, a paper outlining the ideas of Active and Passive transductions was written. The authors found an aspect in TRSR, namely the conversions with and without recognition, that could not be described in SS with the tools at the time. A direct consequence of this comparison was the further development of one of the frameworks. See Ref. [22] for the paper that was a direct result from this study.

We thus suggest that these types of comparisons between similar theoretical frameworks are good in several aspects; they provide an overview of both theories and aim to pinpoint the difference between them; they also help researchers discover aspects in each framework that may need to be improved or added.

Based on our findings, we are also confident in that both frameworks can be used in tandem to provide a deeper description of the learning situation that captures the two different perspectives.

Another very important implication of this comparison is the realization that we can, by cross-examining different concepts of different theoretical frameworks, begin to discover fundamental pieces of what learning entails, or what makes learning possible. If the same ideas, or concepts, are present in both frameworks, this indicates that the concept itself may represent a fundamental piece of whatever the frameworks aim to describe. However, it may just be a necessary result based on some common assumption of the frameworks as well.

VIII. ACKNOWLEDGMENT

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Paper VI

Creating representations using Social Semiotics and Variation Theory - A case study

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Social Semiotics describes the learning situation based on the communication between the learners through the use of semiotic systems and semiotic resources. The systems and the resources aim to describe what is used to learn, such as text, images, formulas, graphs, laboratory work and more. Each semiotic resources provides access to some of the disciplinary relevant aspects of the learning goal. Social semiotics have provided us with a language to discuss these resources, but we want to use the ideas presented within social semiotics to construct a new semiotic resource. The research here is two-fold, the first is to test the ideas of social semiotics to see if they can used as a guide when constructing new semiotic resources.

The semiotic resource in question is a representation of thermal energy that aims to address some misconceptions that relates to student understanding of temperature and heat. The representation represents thermal energy as a volume with the relevant aspects as the dimensions, with temperature as the up-dimension. With the representation we can address a number of concepts within heat diffusion and equilibrium.

We introduce the representation to a group of physics-teacher-students to study how they use it for their own understanding, but also if they see that they could adopt it for their future classes.

Keywords: TO DO

I. INTRODUCTION

Representations are used everywhere in physics education and students must learn to read, construct and use them in many different situations. The multimodal framework of *Social Semiotics* (SS) and the *Variation Theory of Learning* (VLT) both attempts to describe how representations are used and how representations should be used for discernment of critical aspects and learning. Together, these frameworks have been used successfully to analyze different learning situations [1–6].

SS describes how *semiotic material* is represented in different *semiotic systems* using different *semiotic resources*. For example, when we move from a formulaic representation of velocity to a pictorial representation of the same velocity, we preserve the semiotic material in the transduction. VLT describes types of variation of different aspects of a concept, such as varying the magnitude of velocity while keeping other aspects the same. The different types of variation and experiencing representations in different ways allows for discernment of different aspects and learning.

However, neither SS or VLT describes how to construct representations, but rely on already constructed and established representations from the discipline they are deployed in. In physics, we have established ways to draw vectors, to make graphs, and even some established gestures such as the right-hand-rule. But, can we use the constructs and ideas presented in both SS and VLT to produce some guidelines when a student or teacher may want to construct a new representation.

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In this paper we construct a new representation for thermal energy and analyze how students use this new representation to discover potential problems and pitfalls, in the usage and the construction of the representation.

II. BACKGROUND

The construction of representations is not a new area of research (see e.g., [7]). However, the same approach have not been undertaking within SS and VLT.

III. METHODOLOGY

A. Theoretical approach

Based on the constructs within SS and VLT, a number of guidelines can be identified when constructing a representations. See SEC V for this list.

B. The representation

The constructed representation, seen in FIG. 1, aimed to represent the formula for thermal energy, $E_{th} = C_v m \Delta T$, as a three-dimensional volume where the three variables C_v, m, and ΔT can be varied. The aim of the representation was to construct a new representation of the formula that allows for easy discernment of the relationship between the three parts. The student can construct this thermal-energy volume for different materials to see how they differ. For example, the thermal energy for a kilogram of water at $40C^{\circ}$, in a room at room-temperature, is larger compared to a kilogram of copper at $40C^{\circ}$ in the same room. Using the volume representation, the students can easily discern the difference in thermal energy.

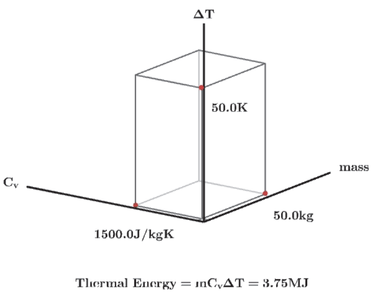

FIG. 1: The representation of thermal energy that the participating students had to discuss and use during the interviews.

The representation only captures the specifics of the formula and does not attempt to represent a broader view of thermal energy. In reality, the specific heat capacity, C_v, depends on the temperature and is not a static value. Although, this can be incorporated in the representation, it was not applied in this study for two reasons: The representation was designed to be easy to understand and use, but it was also to observe if students would recognize the flaws of the representation itself.

C. Case study approach

The case study consisted of X group interviews where the participants discussed the concept of thermal energy and used the new representation to solve tasks involving thermal energy.

D. Data Collection

To be able to perform a comparison on how the two theoretical frameworks are applied to analyze a learning situation, we gathered data where students used representations to discuss and explore the concept of thermal energy. The aim of the data collection was not to investigate the students' understanding, but to capture data that has a wide range of usages of representations by the students.

The data collection took place during the Covid-19 pandemic and university education was performed remotely.

1. Participants

The participants that took part where first year physics students and first year physics teacher students in Sweden. The participation was voluntary and the participants where recruited through a physics course during their first year.

2. Digital group interviews

The interviews where done with two students at a time over Zoom™. During the interview, the students where encouraged to discuss the task at hand, but also to go on different tangents where they produce or used different representations. Using the Zoom™ Annotate function, the students could draw, point and write directly on the PowerPoint where the tasks were presented, see FIG. 2 for an example of this.

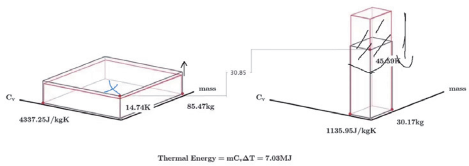

FIG. 2: Two students draw in Zoom™ how they thought the thermal-energy-volumes would change when the two objects interact with each other through heat-transfer. The heat-transfer were then simulated until the the two objects reached equilibrium with each other.

The PowerPoint presentation, the students faces and discussions, and the dynamic annotations where all recorded using the Zoom™ record function.

E. Quality Assurance

The questions and tasks used in the interview were designed through discussions with outside experts to ensure that the questions and tasks would provide the opportunity to capture the students' usage and construction of different representations. We also discussed with lecturers that regularly used Zoom™ and its annotate function in their teaching to find the limitations and pitfalls with the technology. Each participant only took part in a single interview, this limited their time to recall or reflect on the questions over a longer time, however, they were all encouraged to contact the research team at any time with more thoughts or questions.

The Zoom™ record function provided audio and video of each participant, optimized for the human voice and look, which allowed for easy and accurate multimodal transcriptions. The video allows for an accurate understanding of the flow of the discussion and provides the possibility to pick up nuanced expressions that may affect the meaning a participant attempts to convey.

IV. DATA ANALYSIS

The data was analyzed using the constructs from social semiotics to identify the students use of the representation. Translations, transductions, relevance structure, discernment, and variation were identified in the data to guide the construction of different principles when creating new semiotic resources.

V. RESULTS

Based on the data, we can say that the students could easily perform transductions from an already established semiotic resource within the discipline, $E = mC_v\Delta T$. They also described how they may apply the same idea to other formulas that use three variables in a similar configuration. Thus, the representation had synergy with already established semiotic resources within the discipline.

A. Theoretical guidelines

Below follows a list of guidelines that emerged from the theories of SS and VLT for constructing new representations.

Variation: The representation should allow for easy variation of disciplinary relevant aspects.

Translation: The representation should be situation within a semiotic system that can be adapted for different purposes, such as turning the 3D-graph into 2D, or by adding colors or changing other aspects.

Transduction: The representation should allow for easy transduction to and fro other useful representations of the same concept. Such as a known formula and a 3D-graph of it.

Discernment: The representation should allow for easy discernment of disciplinary relevant aspects by aiming to reduce extraneous noise in the representation.

Fluency: The representation should be in a semiotic system where the student is proficient at using.

B. Study guidelines

Student Knowledge: Students' prior knowledge will affect what they discern from a representation.

Misconception: The representation may introduce misconceptions. In our example representation, FIG 1, we represent an energy as a volume. Students may think that an object with large thermal energy correspond to a object with large volume.

Universality: Students may think that the representation is universal and try to apply it in other situation where it may not be applicable.

C. Zoom and interactive whiteboards

The method to collect data, using group interviews in Zoom, is relatively new way gathering qualitative data to be used in physics education. However, it was a necessity due to the Covid-19 pandemic during 2020 and 2021. From the data collection sessions we made the following observations that other researchers may want to be aware of if they plan on doing similar studies.

Training: The students should have some experience in using the Annotate function before coming to the interview or else the tool may hinder instead of aiding the students construction of semiotic resources.

Multimodal-media: Thanks to the screen share function in Zoom™ it is possible to create an environment where students can draw and write directly, and collaboratively, in the learning material. In FIG. 2 we see student drawings on top of a video file embedded in a shared PowerPoint. This interaction creates a space that is highly multimodal and dynamic.

Restrictions: Zoom™ restricts the use of body language and gestures for use in communication, especially when the screen is filled by a PowerPoint.

VI. CONCLUSIONS

To avoid the buzzwords from the frameworks, the guidelines have been rewritten and are presented below:

- The new representation should be situated in a communicative system the student familiar with. Depending on the students knowledge, these can be: formulas, pictorial diagrams, gestures, speech, graphs and more.

- The important aspects should be easily seen, through variation and/or the students prior knowledge of how to read this type of representation.
- The new representation should fit with other, already established, representations within the discipline and the movement between old representations and the new representation should be painless.
- Students' prior knowledge will affect what they read from the representation. If the students come from a course in electromagnetism, they will be primed to see aspects or concepts that can be found within electromagnetism, such as 3D-coordinate systems using the right-hand-rule.
- The limitations of the representation must be made apparent to the student.

VII. IMPLICATIONS

VIII. ACKNOWLEDGMENT

We wish to thank Prof. Ann-Marie Pendrill for her invaluable input on the initial representation and for the insight into different problems the students may encounter while using it. We also thank Dr. Bor Gregorcic for sharing his knowledge of using Zoom™ and the Annotate function as a learning and interactive tool.

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Paper VII

On the Dynamics of Semiotic Resources

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In social semiotics, semiotic resources are used to construct and communicate meaning. In the physics discipline, these are graphs, diagrams, formulas, texts, and more. Based on previous research, we also know that the manipulation of these semiotic resources allow for discernment of disciplinary relevant aspects which provide opportunity for learning. By taking a particular theoretical concept and representing it in a new way, new insights about the concept may emerge that allow for new methods or applications of the concept itself. In this paper, we represent semiotic resources in a new way to gain insight into their dynamics. A mathematical toy model is introduced to describe semiotic resources and how to compare semiotic resources with each other. The mathematical framework used in this paper is based on a dual-space setup which allows us to separate concepts from the representation of the concept. The mathematical framework introduces operators to describe changes to semiotic resources and changes to the discernibility of aspects. The student is also introduced as an operator and described in terms of how it discerns aspects from semiotic resources. As a student interacts with semiotic resources they may discern aspects to understand the physics under investigation. The learning situation is modeled as a set of discernible aspects that the student can move between. From this we can identify concepts from Social Semiotics and Variation Theory of Learning such as student's Relevance Structure and Disciplinary Relevant Aspects. The toy model provides a basis for formally describing the dynamics of semiotic resources used in physics education.

Keywords: Social Semiotics, Semiotic Resources, Physics Education Research, Theoretical Framework Development

I. INTRODUCTION

Imagine a physics classroom where a teacher intends to introduce the physics concept of 'Velocity' to their students. They want to construct a learning situation which they anticipate will facilitate the discernment of important aspects of the concept, such as 'Magnitude', 'Direction' and 'Change in position with respect to time'. In this paper we use discernment as presented in [1]: discern means to notice and think about in ways that lead to meaning-making such as realizing that a 'change in position with respect to time' is 'Velocity'. For such a teaching-learning situation, a good way to analytically look at such a teaching-learning situation is to give consideration to how meaning is communicated by the teacher and how meaning is constituted by their students using this communication [2–5]. The point of departure for this article is to introduce a unique way to focus on how students' interact with the communication and what this reveals that is new about the dynamics of semiotic resources for the optimization of learning outcomes. To do this a mathematical model is proposed and illustrated viz-a-viz the 'how' and 'what' of engaging with a number of meaning-making *semiotic resources*, which in physics education are communicative 'texts' such as spoken and written language, graphs, diagrams, formulas and gestures [4, 6–12]. The significance of this positioning raises the question: will the students discern all the aspects the physics discipline considers to be relevant for being able to understand and use a particular concept or construct appropriately? By 'aspect' we mean " a particular part or feature of a situation, an idea, a problem, etc.; a way in which it may be considered" [13] which includes quantities, shapes, relationships and dynamic effects. A necessary starting point is the need for teachers to be able to insightfully use a particular set of semiotic resources in ways that potentially best enhance the potential to discern the 'disciplinary relevant aspects' [14, 15].

In this article, we propose a new and novel way to think about semiotic resources and how they can be examined in different learning situations. This novel framing is based on a mathematical formulation of semiotic resources and how this can be used to generate insight into how disciplinary relevant aspects can be made 'visible' through the design and use of specific semiotic resources. Significantly, our proposed formulation makes it educationally possible to mathematically reconstruct several key ideas that are epistemic for the highly successful learning theory anchored in *Social Semiotics* [4, 16, 17] and *Variation Theory of Learning* [18–20] (such as disciplinary discernment, variation of aspects, relevance structure, and disciplinary and pedagogical affordance).

The idea for the framework presented in this paper emerged during the data analysis in [21, 22] where FIG.

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1 become a key part. While both representations in Fig. 1 are constructed from the exact same underlying heat diffusion simulation, there is a clear difference in the way they convey information. In order to explain why the meaning-making potential in each representation in FIG. 1 differed we needed a new way to describe what differentiated them form an educational perspective. By using the ideas of Disciplinary Affordance [23], Pedagogical Affordance [24], Disciplinary Discernment [1, 25] and Disciplinary Relevant Aspects [14, 15], we could qualitatively compare the two representations with respect to their ability to allow for the construction of meaning with regards to the discipline of physics. It was through this qualitative comparison the idea to construct a quantitative way to compare and analyze different semiotic resources evolved.

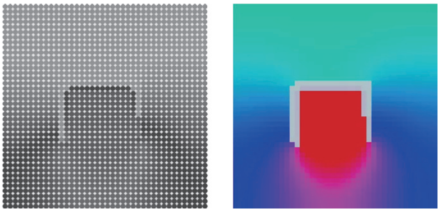


FIG. 1: A 2D heat diffusion simulation's visualization is modified by adding color and changing the visual shape of the elements to improve the discernment of the important aspects, namely the temperature distribution and elements with low thermal conductivity.

From the qualitative comparison came the idea that we might be able to construct a quantitative approach to applying the ideas to compare different semiotic resources.

The mathematical framework presented in this paper is a toy model [26]. A toy model in physics is a model that tries to be as simple as possible to model a specific or a few key features of a system. Our model aims to capture the idea of comparing semiotic resources and what follows from the description of semiotic resources.

The article begins with an overview of Social Semiotics and how we use some of the fundamental theoretical constructs found within it and developed within Physics Education Research (PER). We then introduce the base of the mathematical framework in SEC. III. The framework is based upon a Dual Space using Dirac's [27] bra-ket notation. This is followed by an introduction of the operators that introduce change to the semiotic resources and how to think about changing semiotic resources. We then introduce the notion of unpacking and what we refer to as 'base aspects' within the mathematical framework in SEC. V. In SEC. VI we describe the learning situation and how to model the students' and the discipline's *relevance structure*, that is, what is considered to be important and necessary for dealing with a given situation [28–30], [19, p. 143-144].

II. SOCIAL SEMIOTICS

In 1978 Micheal Halliday [17] introduced the idea of *Social Semiotics* (SS) as a way to describe language and parts of language from an interpretive and meaning-making perspective. Social Semiotics have further been developed into a multimodal framework [16, 31, 32] and a summary of the framework was presented by Airey & Linder [4] in 2017. Airey & Linder (2017) define SS as: *"the study of the development and reproduction of specialized systems of meaning making in particular sections of society."* and have applied SS in physics education research [1, 15, 21–25, 33–38].

A. Semiotic Resources

In SS, communication within a discipline is done using semiotic resources [4]. In the physics discipline, these resources are typically manifested as graphs [39], formulas [40], books, lectures, and many more representations [10, 37, 41]. Each semiotic resource is designed to contribute to the intended meaning-making process.

B. Affordances

Affordances, as used by [10, 23, 24, 34], describes what a semiotic resource affords the learner, teacher, or researcher. Affordances, be they either pedagogical [24] or disciplinary [23] affordances, describe how appropriate the semiotic resource is for a specific situation.

In this article, we are going to connect affordances with the possibility to discern aspects in a learning situation. If a semiotic resource provides the possibility for discernment of a specific aspect, we identify this as the semiotic resource having the affordance of that aspect. This is a lower level approach to affordances, compared to [10, 23, 24, 34], but it will allow us to formulate a mathematical description of the term. This use of affordances reflect a more static view of affordances, whereas the disciplinary and pedagogical affordances of [23, 24] reflects the more dynamic uses of semiotic resources. We approach the dynamics of semiotic resources through the introduction of operators.

C. Disciplinary Discernment and Learning

Disciplinary Discernment, and the Anatomy of Disciplinary Discernment [1] (ADD), plays a vital role in the evaluation of students ability to discern disciplinary relevant aspects. Novices are not expected to discern all the relevant aspects that experts can do and the ADD provides a hierarchy that describes the disciplinary discernment from novice to expert.

In the model presented in this paper, we will describe the student as discerning the disciplinary relevant aspects that semiotic resources affords. However, the reader should be aware that the discernment in a real setting is much more involved than the simple projection operation presented in this paper.

D. Disciplinary Relevant Aspects and Learning goals

In [14] and [15] Fredlund *et al* presents the idea of *Disciplinary Relevant Aspects* (DRAs). DRAs are the aspects that the discipline has deemed important in a given learning situation. For example, in [29] Eriksson *et al* identify the DRAs for circular motion.

For the mathematical formulation in this paper the learning goal of a learning situation is taken as being in alignment with the DRAs of the situation. This alignment allows one to match learning goals to the discernible aspects of a learning situation and measure how well they match.

III. MATHEMATICAL FORMULATION: WEIGHTED ASPECTS AND AFFORDANCES

In a learning situation, for any given concept, one must identify the DRAs of the concept and separate them from the aspects that are not important for the intended learning goals.

This is true for researchers in any disciplinary based education research field, but also for researchers within the discipline itself. Both types of researchers must be able to discern the DRAs for a given concept before they can start engaging with it in a productive and meaningful way.

In a learning situation, aspects of a concept are presented using different SRs [4], such as specific textbooks, presentations, equations, graphs, laboratory activities and so on. Each SR provides access to one or more aspects of the concept. And as evident in FIG. 1, whereas two different SRs can be crafted from the same information they can provide different degrees of access to the DRAs of the concept. Another way to describe it is that different SRs provide different possibilities for discernment of DRAs. To be able to construct the mathematical formulation that we propose, we begin by defining a SR, $|R\rangle$, in the following way,

$$|R\rangle = \sum_{0}^{n} \overbrace{k_n \underbrace{|A_n\rangle}_{\text{Aspect}}}^{\text{Affordance}} , \tag{1}$$

where $|A_n\rangle$ is the different aspects of a SR, i.e., the meaning that can be discerned from it. With the addition of a weight in front of the aspect, k_n, we obtain a measure of how well this aspect can be discerned from the resource which we call its affordance An affordance is thus a weighted average. This new way of approaching affordances preserves the essence of the 'affordance'-concept as a meaning-making potential afforded by the environment [4, 42, 43] at the same time as it allows us to formula our mathematical description of the term.

In FIG. 2 the two images from FIG. 1 have been broken down into a number of aspects (including their relative weightings) to illustrate how a change in the affordance will affect how discernible some aspects are. As such, both pictures include the same aspects, but with different affordances since the affordance is a function of how well something can be discerned. Whereas any single SR may, in theory, provide access to all the DRAs for a problem, some aspects may be *appresent* [1, 34] and thus so hard to discern (low k_n) that the SR is rendered useless in a situation where meaning is to be extracted from it. For example, in FIG. 1 the discernibilty of some aspects, such as 'temperature distribution' and 'heat conductivity', have been increased. This increase in discernibility was done by adding colors that are coupled to the temperature and by changing the shape of the elements to reduce clutter. For a SR to be useful in a given situation, it must contain the discernible aspects that correspond to the DRAs, but also have a high affordance of these aspects [24].

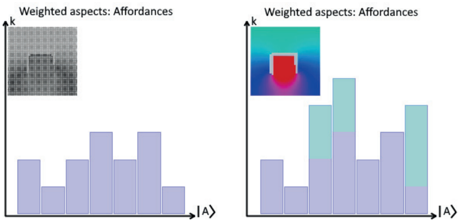


FIG. 2: Here we go from a black and white representation to a colorful representation of a heat diffusion simulation. The addition of color has made some aspects more discernible as is represented using the histogram below the image. The k-value, or weight, of different aspects changed when we added color to the representation.

This way of describing aspects and affordances, using the suggested mathematical formulation, is a new and novel way of describing these concepts. We realize and acknowledge that the reader may be unfamiliar with this type of presentation and that it may seem strange at first. However, it does conform to established ways in which the terms are used. For instance, in Ref. [43], which is seen as the first description of the term, Gibson describes affordance in two ways. The first way states that affordances is what the environment affords an agent that interacts or experiences the environment. For example, a person may think, or be urged to, 'drink' when seeing a glass of water. The affordance will depend on the agent and its capabilities; a fish will not look at a tree and think 'climb' but a monkey probably will. On the other hand, the second way Gibson describes affordance is to treat them as independent of the agent. The agent only discerns those affordances that it has evolved, or been educated, to perceive. With the implication that if we train a fish to climb, they will think 'climb' when they see a tree because they have been trained to discern that affordance.

The concept of affordance has further been extended in social semiotics to distinguish between disciplinary and pedagogical affordances [4, 42]. In turn these describe what different SRs afford - for the discipline in terms of disciplinary knowledge and for the students in terms of pedagogic use. In a learning situation a student must acquire the ability to discern and use the disciplinary affordances of the different SRs. The student does this through the process of unpacking (see SEC. VI and Ref. [1]).

Eq. 1 captures the essence of the second description in Ref. [43], that of an affordance being independent of the agent and part of the semiotic resource itself. The mathematical equation describes a SR that affords the discernment of different aspects. Different SRs afford different aspects and even if they afford the same aspects they do so to a varying degree. However, the affordances does not depend on an agent or interaction with an agent. Later in this article we will introduce our agent, the student, and show that we can model the student to only discern some of the aspects that the SR affords. This discernment will depend on the student's educational and experiential history. We do not incorporate the ideas of disciplinary- or pedagogical affordances in this paper, but are hopeful that they may be incorporated as different structures or combinations of affordances in the future.

A. Dual spaces and measurement

In Eq. 1 the aspects, and the SRs themselves, are written using Dirac's bra-ket notation [27] used to simplify quantum mechanical calculations by separating them into states and operators. The bra-ket is part of a dual space mathematical framework where each 'bra' has a corresponding 'ket' and the 'bra's span the same space as the 'ket's. The dual space follows the requirement

$$\langle n|m\rangle = \delta_n^m \tag{2}$$

meaning that two states, $\langle n|$ and $|m\rangle$, are a dual if $m = n$ resulting in $\delta_n^m = 1$. We suggest that it is yet unknown how to construct the dual to a SR $|R\rangle$. However, we are going to assume that there exists a dual, $\langle L|$, to any SR such that $\langle L|R\rangle = 1$. Put another way, we are going to assume that there exists some way of moving from a SR $|R\rangle$ to its dual $\langle L|$, giving

$$\hat{F}(|R\rangle) = \langle L| \tag{3}$$

with the opposite operation

$$\check{F}(\langle L|) = |R\rangle\,. \tag{4}$$

However, we must now argue for why we expect that these functions exist and to do this we must understand what $\langle L|$ represents when used in this situation.

1. Learning goals

To understand this dual space, one must understand what the $\langle L|$ and $|R\rangle$ represents. In any given learning situation a particular student will use one or multiple SRs to solve and/or to understand a problem. However, the question here is how one can know if the student has discerned the DRAs of the situation or not? To answer this question one must perform a test, either by observations, interviews or actual exams. Such tests are used to see how well the aspects, learned by the student, match the learning goals of the situation. This is our 'bra' to our 'ket'. The learning goals of a situation is $\langle L|$ and for each situation there are different learning goals.

However, how can it be argued that the learning goals and the basis states spanned by the discernible aspects are somehow connected?

To answer this question we turn to Fredlund *et al.* [42] who introduce the concept of Disciplinary Relevant Aspects (DRAs). A DRA is an aspect of a situation or problem that the discipline has deemed important or is required to understand the situation or problem. For example, to be able to calculate the forces on a falling ball using a free-body diagram, the DRAs include the direction of the force(s), the size of the force(s), and the identification of the source of the force(s). The learning goals, the $\langle L|$, for a given situation is thus given by the DRAs of the situation. The identification of learning goals and DRAs means that both bases of the dual space are given by aspects. The $|R\rangle$ is spanned by the aspects that can be discerned from a particular SR and the $\langle L|$ is spanned by aspects the discipline finds relevant for the situation, the DRAs. If a SR perfectly matches the DRAs of the situation we obtain a perfect alignment between them which gives

$$\langle L|R\rangle = 1. \tag{5}$$

However, this perfect match is possible only in an ideal scenario and is thus not realistic. In a realistic scenario, where the SRs and the learning goals do not align fully, we are more likely to get

$$\langle L|R\rangle < 1. \tag{6}$$

A result less than one is thus an indication that the learning goal does not match the SRs used or vice versa. This is expected in a real-world scenario. For instance, a semiotic resource such as a mechanics textbook is not expected to capture all the intricacies of the subject (i.e. the learning goals). The mechanics textbook needs to be complemented with a variety of other SRs including, for example, lectures, group work, practice exercises, laboratory and project work. With each SR chosen with the specific intention of matching one or more DRAs of the learning goal.

2. *Learning goals and real-world situations*

The learning goals, $\langle L|$, should be thought of as the platonic idea (see Ref. [44]) of the concept, whereas the SR, $|R\rangle$, should be seen as the real-world situation from which the DRAs may be discerned. Thus, the learning goal is the pure concept and the resource is the messy real life. In FIG. 3 we attempt to show this distinction. A real-world situation will probably provide many more aspects than the learning goal asks for. For example, whereas a velocity-time diagram has some DRAs that the discipline requires the student to discern and learn, the diagram drawn on the whiteboard by the lecturer may inadvertently introduce discernment possibilities of non-relevant aspects. For example, the velocity-time plot may have been drawn with a thick, green whiteboard marker. Clearly, the aspects 'green' and 'line thickness' have no part in the DRAs of the velocity-time diagram, yet the real-world diagram includes these aspects for students to discern.

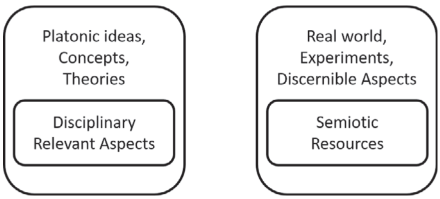


FIG. 3: On the left we have the ideas, theories and concepts used within the physics discipline and on the right are our representations of the DRAs and the SRs.

3. *Measuring and Assessments*

In quantum mechanics, or other systems where a dual-space approach is employed, the 'ket's represent the state of the system and the 'bra's is the basis of the measurement. The 'bra's define how we measure our state and the result is a measure of how well the system matches the measurement basis. In the context of the physics discipline, we can interpret this measurement as an assessment, examination, or test, that attempts to assess how well our SR match the learning goal. This is also the argument for why the $\hat{F}$ and $\check{F}$ functions exists. The basic assumption for our assessment is that it is possible to measure how well our SRs afford the correct DRAs. If we do not believe that we can construct a set of SRs that correspond to the desired learning goals, our idea that we can assess student performance will fail. Thus, there must thus be a connection between the learning goals and the SRs for an assessment tool to prove valid.

B. Constructing a learning environment

As Fredlund *et al.* suggested in [45] and Eriksson *et al.* expanded upon in [29], if one wishes to create a learning environment that provides meaning-making opportunities for the student, one should do the following:

- Identify the DRA for the situation
- Choose appropriate semiotic resources
- Identify students' relevance structure (see SEC. VI)
- Provide variation of critical aspects to allow for discernment

Using our mathematical terms we can rewrite the first two conditions as follows:

- Identify the $\langle L|$ for the situation
- Choose appropriate semiotic resources: $\check{F}(\langle L|) = |R\rangle$

The last two conditions on the list will be expanded upon in SEC. IV and SEC. VI where we begin to manipulate the SRs with operators and we study the learning situation in which the SRs are applied. Further, we also foresee that it is possible to match the mathematical structure described above with ideas from physics education research. Which will allow us to continue our analysis for further insights in the following sections.

IV. OPERATORS

In this section we introduce the concept of operators (e.g., [46, chap. 3.3], [47, 48]) and modifications to SRs, which will allow us to describe and discuss changes to SRs, such as the modification depicted in FIG. 1.

Operators act upon our SR, or more precisely, on its discernible aspects or the discernible aspects weights by changing them. But operators may be more complex than that, such as extracting, or foregrounding, a specific aspect. Below we introduce the 'student' operator that represents the student interacting with the resource.

In a learning situation, an operator is any action that changes the SR. It does this by acting upon one or more aspects of the resource. For example, a lecturer (the operator) draws her students' attention to a specific aspect of a diagram. In so doing she is seeking to act upon the resource in ways which will enhance their ability to discern the DRA of the resource. The effect of an operator may also be time dependent – when the lecturer stops pointing at the diagram, the action ceases and the students may no longer find it as easy to discern the DRA as effectively as before.

A. Student

The most important operator in the model is the student (S), who can be inserted between the learning goal, $\langle L|$, and the resource, $|R\rangle$:

$$\langle L| S |R\rangle = k_s \tag{7}$$

where k_s is the expectation value of the student after they have interacted with a certain resource, $|R\rangle$, and is evaluated in an exam, $\langle L|$. The expectation value k_s is a measure of how well the student discerns aspects from the resource and how well the discerned aspects matches the learning goal. We can also interpret this in another way:

$$S |R\rangle = |R_S\rangle \tag{8}$$

which is the combination of the resource and the student. Only the aspects that the student has discerned are left in $|R_S\rangle$ after the operator, S, has operated on the resource. However, we can also interpret the S operator in another way:

$$\langle L| S = \langle L_S| \tag{9}$$

where the learning goal is changed instead of the resource. We can say that the learning goal has been adjusted for this specific student. The total operation, with measurement, is thus:

$$\langle L| S |R\rangle = \langle L_S|R\rangle = \langle L|R_S\rangle = k_s \tag{10}$$

We would like to make the reader aware that we do not know of what form k_s has. It may be a number, or something more complex. This is because we have yet to define what an aspect, or DRA, actually is in mathematical terms. This is presently beyond the scope of this article which is limited to introducing the overlaying mathematical structure in which DRAs can be operated and manipulated. As we further develop this framework, by incorporating more and more phenomena into the model, we can foresee that a better understanding of the underlying structure will emerge and we will be able to make predictions on the nature of k_s and its states.

B. Changing the resource

Within multimodality frameworks [31, 32], such as Social Semiotics (SS) [4], and the Variation Theory of Learning (VTL) [18, 19], is the notion of changing or shifting resources to increase the possibility for meaning-making. The changes described in SS are referred to as *translation* and *transduction*. Translation describes a shift of the aspects of a resource, but the resource stays within the same semiotic system [4, 10]. For example, rewriting a research article into a book chapter or a popular science article should aim to preserve the semiotic material of the resource. The translation stays within the same semiotic system, such as text, images, and graphs. The research article is a text and is rewritten to another text. Transduction, on the other hand, describes a shift of semiotic material between different semiotic systems [4, 6], such as moving between a function, $f(x) = x^2$ and its graphical representation. The semiotic material has been shifted and modified, into a new semiotic system.

Variations, translations and transductions are all well documented and described by theoretical frameworks [4, 18, 31]. We can thus assume that it is possible to modify a SR and that this change has some effect on the meaning-making process of the student. Within this model we relate the discernment of aspects to the possible meaning-making by the student; if a student can not discern an aspect, then that aspect can not be used in the meaning-making process.

We model these changes as operators that act upon a SR to create a new SR. In the following formula, we act upon the resource $|R\rangle$ with the operator O to produce an new resource $|R_O\rangle$:

$$O |R\rangle = |R_O\rangle . \tag{11}$$

We can interpret this in two ways; either we have just modified an existing resource or we have constructed a new resource based on the old one. Both interpretations are valid and the mathematics does not distinguish between them. The mathematics does not constrain how large or how small the operation must be. For instance, it could be an operation that adds only a capital letter to a text, or it could transform the text into complex mathematical formula. Large or small, operations that result in a change in aspect(s) by implication also result in a change in the discernment possibilities of the aspect(s).

By way of example, in the heat diffusion simulation visualization displayed in FIG.2 the operation involved the addition of the aspect of 'color' and coupled the color to the value of the temperature. In FIG. 1, as depicted graphically, we see how some of the weighted aspects increased following the modification of the resource.

1. "This pen is a rocket"

Operators and modification to resources are any type of effect that changes the aspects or the discernibility of the aspects. An instructor pointing to a specific part of a diagram to make sure that a specific aspect of the diagram is seen (discerned) by the students is a modification of the SR. In FIG. 4 a person uses the phrase "This pen is a rocket" to set the context of the discussion and to allow them to have a tangible object to project their ideas upon. The phrase should be seen as an operation that acts to increase the discernibility, the weightings, of certain aspects as well as introduce new aspects that relate to rocketry.

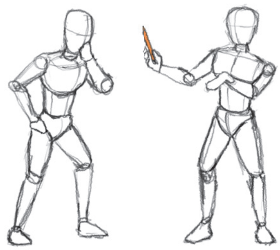


FIG. 4: By saying the phrase: "This pen is a rocket" we perform an operation on the SR 'pen': $S_{rocket}\,|pen\rangle$ to add some aspects to it that can now be discerned. The new SR, that the person on the left is interacting with, is thus $|pen_{rocket}\rangle$ and affords discernment of new aspects because it has been modified.

Thus, an operation or modification of a SR is not just changing the wording of text to make it clearer or moving between different semiotic systems. Operators are dynamic and the lecturer may employ a range of them - speech, gestures, the laser pointer and so on, to help the students discern aspects over the course of a lecture. A lecture can be thought of then as a system of aspects that the lecturer seeks to change the discernibility of by utilizing different operators. It is the task of the lecturer to increase the discernment possibilities of the aspects being considered and where necessary, to facilitate smooth transitions between different semiotic resources. Take for example, when a lecturer introduces the concept of acceleration following on from a discussion on velocity. This could be done by simply stating that: "Acceleration is $\partial^2\bar{x}/\partial t^2$". Whilst this statement is true, it is quite likely that aspect 'position', or 'x' will be low on the students' discernibility scale. This is because the switch to acceleration requires an abrupt jump in the students focus and the lecturer needs to be mindful of this fact. Thus, in order to preserve the discernibility and continuity of these aspects, it would be more useful to introduce acceleration as a change in velocity brought about by varying the magnitude and/or direction of the velocity. Presented in this way, the discernibilty of 'acceleration' is slowly increased as we operate on the already discerned aspect 'velocity'. This ensures a continuity of discernment and aspects and follows the idea of *the spiral of teaching and learning* by Eriksson [1, 49, 50], where one returns to the same concept several times in order to offer deeper discernment possibilities for the student.

C. Combining Operators

Several operators may be used one after the other to describe a longer chain of events. Take for example when a PowerPoint presentation is modified and handed out to students as a set of printed slides. The students now experience a SR whose aspects have different levels of discernibility compared to the presentation. The new resource, the printed form, can be described as follows:

$$SMT\,|R\rangle = S\,|R_{new}\rangle \tag{12}$$

where T and M are the modification of the PowerPoint and the conversion into a printed format respectively. The operators have acted upon the the SR to create a new SR. However, we may instead combine the operators SMT into a new operator that operates on the SR:

$$SMT\,|R\rangle = S_{new}\,|R\rangle \tag{13}$$

where we interpret that the operators have modified the students' ability to discern aspects from $|R\rangle$. We now have two different representations of the same situation: $S\,|R_{new}\rangle$ and $S_{new}\,|R\rangle$ and we see two ways of interpreting the situation through the PowerPoint presentation and through the printed slides. Either way we have a new SR, $|R_{new}\rangle$ that affords new discernment of aspects, or the student has learned to discern more. The duality of interpretation is also captured in the act of discernment that is itself dependent on both the student and the SR.

So, the use of the operators is twofold, either we can identify them as affecting the student and changing the student's discernibility and hence degree of understanding, or we can interpret them as changing the resources that the student interacts with to increase the discernibility of certain aspects of the resource. In this framework, both scenarios are described by the same mathematics and we can say that they are just two sides of the same coin.

In FIG. 4, we may interpret the interaction in two ways. Either we have constructed a new SR that affords the discernment of new aspects, or we have influenced the student to discern more aspects. Mathematically we can say that these two interpretations can be described in the same way.

D. Order of the operators

The order in which the operators are written is important. We can not assume that $MS\,|R\rangle = SM\,|R\rangle$ because we do not have a complete understanding of what the operators are. In some situations, the order may not be important, but in others it is. For example, in rotations or scaling in Cartesian coordinates - the final system will depend on the order of rotations. The same is likely to be true for the operators in this new approach to Social Semiotics presented in this paper.

In the case of the Flipped Classroom, where the students engage with the material before coming to the lecture and the lecture itself is more of a question and answer session, the order of the operators are reversed. In operator notation we can write these two interactions as:

$$LS\,|R\rangle \neq SL\,|R\rangle\,. \tag{14}$$

On the left-hand side of the equation, we have the situation where the student, S, interacts with the semiotic resource, $|R\rangle$, before the lecture happens and on the right-hand side, we have the reverse situation. From research e.g., [51–53], we know that the Flipped Classroom produces a different set of outcome compared to a normal lecture situation, and we can thus conclude that the order of operators are important. In mathematical terms, we can write this as a commutator that is different from zero:

$$\langle L|\,[L,S]\,|R\rangle \neq 0 \tag{15}$$

where

$$[L,S] = LS - SL. \tag{16}$$

Using this as our base, we can optimize the order in which we employ the operators in our teaching sequence, and in so doing potentially improve the degree of discernment available to the students.

E. Transductive Links as Operators

Transductive links are defined by Svensson & Eriksson in [35] as follows:

A transductive link is any semiotic system that supports the transduction process between two different semiotic systems.

The act of transduction is the process of moving semiotic material from one semiotic system to another and transductive links are used to perform this transduction. In terms of our mathematical model, we can say that a transductive link is a type of operation that changes a SR in such a way that it ends up in a new semiotic system. However, in our mathematical model, we do not have a way of distinguishing different semiotic systems from one another because every SR is described in terms of its aspects and affordances, rather than to which semiotic system it belongs. In FIG. 5, programming is given as an example of a transductive link that moves the semiotic material from one SR to another.

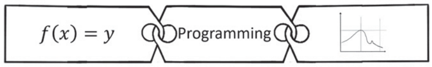


FIG. 5: Programming acts as the transductive link between the formula and the graph. This can be modeled as an operator acting on the first resource to produce the second resource.

Each transductive link affects the aspects of the SR by enhancing and/or filtering them, similarly to the effect that operators have on a SR. We can thus see that the effect of operators, the changing of weights of aspects, is similar to what has already been described in earlier research, as enhancing and filtering of aspects, by [36] and [35] respectively. The mathematical formulation thus expands these ideas to include not just transductions and transductive links but all kinds of modifications of the SR.

F. Measuring the students

A measurement with an operator is called its *expectation value*, k_S, and is computed by "sandwiching" [46] the operator between a learning goal and a SR:

$$\langle L|\,S\,|R\rangle = k_S \tag{17}$$

where the operator, S, is what is measured in the basis of the DRAs and discernible aspects. In this case we are measuring how well a student can discern the aspects that the SR has with respect to the specific learning goal. If the student is capable of discerning all the relevant aspects we have a good starting point. However, this does not imply that the student operator will produce a high expectation value; the students understanding must also match the learning goal. For example, if the student learns everything from a biology textbook, but the learning goal is to ride a bike, we do not expect $\langle bike|\,S\,|textbook\rangle$ to produce a high expectation value. However, if the learning goal and the SR match and the student discerns all the relevant aspects, then we can expect a high value.

We can also measure other operators to learn about their effects on the resource and the learning goal. For example, if we want to understand how a specific operator affects our resource with respect to our learning goal we need to perform a measurement in the same way as before:

$$\langle L| O |R\rangle = k_O \tag{18}$$

and compare it to the identity operator:

$$\langle L| O |R\rangle - \langle L| I |R\rangle = \Delta k_O \tag{19}$$

which we can embed in a new operator, that we can call $\hat{O}$, defined as: $\hat{O} = O - I$. The measurement of $\hat{O}$ thus becomes:

$$\langle L| \hat{O} |R\rangle = \langle L| O |R\rangle - \langle L| I |R\rangle = \Delta k_O \tag{20}$$

where Δk_O is an indicator of how our operator changes the SR with respect to the learning goal. For any operator, except the student, it is desirable that Δk_O is positive or at least indicate an increase compared to before. For the student operator, we expect a Δk_S as close to zero as possible, or perhaps slightly negative. If Δk_S is zero, we can say that the student can discern and use all the aspects of the SR.

V. UNPACKING RESOURCES AND LEARNING GOALS

In [42] Fredlund introduces the idea of unpacking different physics SRs to allow the student access to the relevant aspects for the current situation. This is a very useful notion because it allows us to identify the DRAs of the problem and it help us identify the different aspects that each SR affords.

In Physics a concept may be unpacked into different aspects and depending on how we go about this unpacking we may end up with a large number of them. This is often the case where a concept is represented using formulae, the unpacking of which allows us to discern additional aspects and the mathematical relationship between them. Take for example the mathematical expression of momentum:

$$\bar{p} = m\bar{v} \tag{21}$$

where $\bar{p}$ is the momentum of an object with the mass m and velocity $\bar{v}$. However, we may unpack the formula for momentum further by replacing the mass, m, with density multiplied by volume, ρV, and expanding the vector formulation of velocity into time derivatives of each coordinate:

$$\bar{p} = m\bar{v} = \rho V \cdot (\frac{\partial x}{\partial t}, \frac{\partial y}{\partial t}, \frac{\partial z}{\partial t}) \tag{22}$$

However, to avoid unnecessary unpacking, we introduce the notion of *base aspects*. Base aspects are aspects that we arbitrarily decide we do not wish to unpack further. In order to decide at which point we may comfortably stop our unpacking we must look at the intent of the SR, the learning goals of the situation and the student. For instance, what can we expect the student to be able to discern based on their previous knowledge? If we expect the learner to discern the aspect 'velocity' and 'mass' from the formula $\bar{p} = m\bar{v}$, then we do not need to unpack these terms further. However, if we do not expect the student to discern the aspect 'vector', we need to unpack this aspect to make it discernible for the student. With this in mind, the base aspects are the aspects we expect the learner to discern and understand without help from the present SRs. In FIG. 6 we unpack the concept of momentum into a few chosen aspects and identify the base aspects.

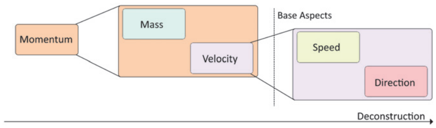


FIG. 6: A concept is deconstructed down to its base aspects, or what we expect the student to discern based on their previous knowledge.

In a formula, we can expand our SR:

$$|R\rangle = a\,|\text{momentum}\rangle = a(b\,|\text{velocity}\rangle + c\,|\text{mass}\rangle) \tag{23}$$

We require different discernibility for the 'velocity' and the 'mass' aspects compared to the 'momentum' aspect and from this we get the new weights ab and ac. Since a, b, and c are all smaller than 1, the new weights are even smaller. That is, if we start with a specific aspect and try to understand how students discern the aspects it is constructed from, we can expect that the discernibility decreases the further it is unpacked. And if we unpack a SR too far, we may end up in a situation where the student will be unable to discern the original aspect,having been swamped with all the other aspects they needed to consider; in consequence they may not be able to see the proverbial wood for the trees.

However, we now need to emphasize that this is for a static SR that we do not interact with. If we interact with it, we change its affordances. For example, if we only show the word:

$$\text{"Momentum"} \tag{24}$$

we should not be surprised when students are unable to discern 'velocity' and 'mass' from the word. We should be even less surprised if they do not discern 'direction', 'magnitude', 'density' or 'volume'. Each step in the unpacking lowers the discernibility of the main concept as we substitute different aspects for unpacked versions of them. The discernibility will become ever smaller: $a_1 a_2 a_3 ... << 1$ as we deconstruct our SRs. When unpacking a SR, we make the base aspects discernible, not by passive expansion of our formula, but by actively operating on it with operators.

A. Simultaneity

The fact that one aspect can be unpacked into other aspects provides an interesting problem. To discern the original aspect from the unpacked aspect, the student must discern them at the same time. In the VTL framework this is described as *simultaneity* [19], or the discernment of several aspects together (typically first individually and then simultaneously). Thus, when we unpack a learning goal, we identify what aspects must be discerned, either separately or together. For the aspect 'momentum', the aspects 'velocity', 'mass' and 'conservation laws' must all be discerned so that they all can be understood together and simultaneously as part of 'momentum'. It is very unlikely that a single SR will afford all the necessary aspects for the learning goal. A carefully selected variety of SRs must be used, and in ways so that they offer appropriate variation of aspects, which can we then connect to our mathematical model through a number of different operators.

VI. DISCERNMENT AND CHAINS

In any given learning situation there are several aspects that may be discerned; some of which are relevant for developing understanding and others that are not. What the student finds relevant for a given situation is called its *relevance structure* (RS) [19, 29] and is further described below. In an ideal situation the student's RS will match the DRAs of the situation. However, the student's discernment of different aspects is fluid and will change as the student engages with the situation. Ideally, during this engagement the student is able to filter out the non-relevant aspects and the student's RS ends up matching the DRAs of the situation. However, this is not always the case, as illustrated in FIG. 7.

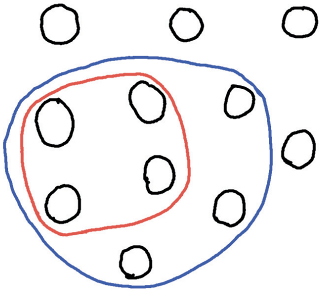


FIG. 7: Out of all the aspects that the students may discern, they typically may only find a subset of them relevant for the situation [19, 29, 54]. These are circled in red. The aspects that the discipline finds relevant are circled in blue, these are the DRAs. A student may discern the DRAs, but also may not find them all relevant for a given situation.

If we were to model this, we would describe the whole learning situation as a sum of aspects and their weightings. However, a number of the aspects are not relevant to the specific learning goal(s) and the task of the lecturer is to employ a number of operators to ensure that the student's RS evolves until it corresponds with the DRAs applicable to the specific learning goal.

A. Markov chains

Let us imagine a learning situation that affords discernment of a number of different aspects (FIG. 8). A student, indicated in red, is shown discerning seven of the aspects in a particular order, ending with the student getting stuck in a loop going between a subset of aspects $4 \rightarrow 5 \rightarrow 9 \rightarrow 8 \rightarrow 4$. This constitutes the student's RS. In contrast, the blue loop, $4 \rightarrow 5 \rightarrow 6 \rightarrow 11 \rightarrow 10 \rightarrow 9 \rightarrow 8$, represents the sequence of DRAs required for a successful engagement with the situation. Something which will not occur because the student's RS does not match the discipline's DRAs. By framing the situation in this way, we can model the discernment of aspects as a Markov chain.

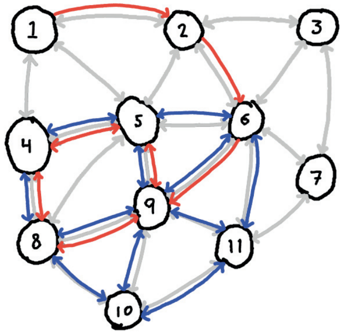


FIG. 8: A certain learning situation consists of many discernible aspects and the student (represented in red) discerns seven of them in a certain order. The student gets stuck in a loop going between a subset of aspects $4 \to 5 \to 9 \to 8 \to 4$. This loop is the students RS. The blue loop, $4 \to 5 \to 6 \to 11 \to 10 \to 9 \to 8$, is the DRAs for the situation. A student's RS should match the disciplines DRAs (see [28]).

A Markov-chain can be represented as a matrix where the probability to discern a new aspect is given by each matrix-element. In a chain with three steps, see EQ. 25, the matrix-representation is given by A:

$$A = \begin{pmatrix} A_{11} & A_{21} & A_{31} \\ A_{12} & A_{22} & A_{32} \\ A_{13} & A_{23} & A_{33} \end{pmatrix} \tag{25}$$

To take n-steps in the situation, we apply the matrix n times, where $A_n = A^n$ describes the situation after n-steps.

When n is large, the Markov-chain often enters a steady-state situation where $A_{n+1} = A_n$. Some chains evolve into an oscillating state where $A_n = A_{n+m}$ repeats after m-steps. This is a combination of periodic states and recurrent states and is called an *ergodic class*.[55].

FIG. 8 shows the point at which a student's relevance structure with its closed loop of aspects $4 \to 5 \to 9 \to 8 \to 4$ has entered an oscillating state that comprises some, but not all, of the required DRAs. The final oscillating Markov-chain for the student is thus a subset of the original Markov-chain.

$$B = \begin{pmatrix} B_{11} & B_{21} & B_{31} & B_{41} \\ B_{12} & B_{22} & B_{32} & B_{42} \\ B_{13} & B_{23} & B_{33} & B_{43} \\ B_{14} & B_{24} & B_{34} & B_{44} \end{pmatrix} \tag{26}$$

$$B_n = B^n = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & B_{22} & B_{32} & 0 \\ 0 & B_{23} & B_{33} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{27}$$

The B_n-matrix is the n-iteration of the B-matrix and it has evolved into a subset of the original matrix. The subset describes the student's movement between aspects as they investigate and solve the situation. This is also known as the embedded Markov-chain (see, for example, [56]).

1. *Relevance Structure*

As noted above, the RS is the set of aspects that the student finds relevant to the situation at hand and is a subset of the all aspects that the student discerns. For a student to find an aspect relevant, they must first discern and reflect on it from a disciplinary perspective; what is referred to as *disciplinary discernment* [1].

It goes without saying that the student's RS may differ from that which the discipline finds relevant in a given situation. In the following example, the student's RS, S_n, does not overlap with the aspects that the discipline finds relevant, D_n.

$$\begin{aligned} S_n + D_n = S^n + D^n &= \begin{pmatrix} S_{11} & S_{21} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & D_{33} & D_{43} \\ 0 & 0 & D_{34} & D_{44} \end{pmatrix} = \\ &= \begin{pmatrix} S_{11} & S_{21} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & D_{33} & D_{43} \\ 0 & 0 & D_{34} & D_{44} \end{pmatrix} \end{aligned} \tag{28}$$

The S_n and D_n matrices do not overlap and this describes a situation where the student will fail at completing the task because they do not find the correct aspects relevant. The student isn't able to discern how relevant the other aspects are on their own, this requires an intervention by the lecturer. The intervention itself is modeled as a change in the student's Markov-chain matrix through the introduction of elements that couple the student's RS to that of the discipline.

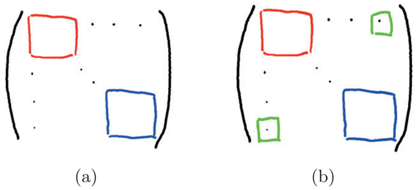


FIG. 9: a) The student's RS (red) is separate from the disciplines RS (blue).
b) An intervention is introduced that connects the two separate areas of the matrix (green).

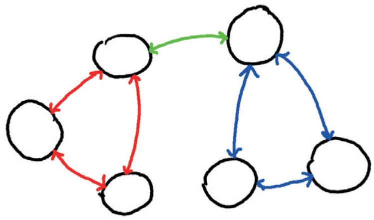


FIG. 10: The student's (red) RS is separate from the DRAs (blue) and an intervention (green) is needed that allows the student to move from one loop to another.

2. Modeling Intervention

Interventions by a lecturer, or another student, can be modeled by a change in elements in the student's Markov-chain matrix. This is depicted in FIG. 9 and FIG.10. Such an intervention is given by the operators described earlier; a variation of an aspect may help the student to discern it and to realize its relevance to the situation. However, it may be hard to move the student's focus from one aspect to another, and here the aspects themselves may be the problem. If an intervention is performed in such a situation, it may not have any effect, but if the intervention is undertaken when the student is focusing on another aspect, it may bring them over to the discipline's RS. If we change our picture to scale the distance between nodes with the probability of the student moving between the nodes, we get a network such as that shown in FIG. 11. In FIG. 11, we have moved the aspects so that those that are related, such as velocity and momentum, are closer together. It is easier to move between aspects that are close to each other, which suggests that this is where we want to perform an intervention if we want our student to discern the new aspect. It is unlikely that an intervention will succeed if the aspect we want the student to discern is unrelated to the aspect they are currently discerning.

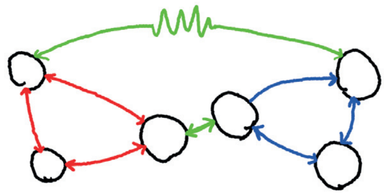


FIG. 11: Some intervention may require a large leap for the student, illustrated here by the longer green path between the top two aspects. Other interventions may be easier to follow for the student, such as the bottom green path. In this representation, aspects that are easier to move between are placed closer together.

3. Diagonalization and Resources

We may perform different types of operations on our Markov-chain-matrix to obtain further insights into our learning situation. The S_n-matrix describes the student's movement between different discerned aspects. Interestingly, this can be described by a standard operation on matrices: diagonalization:

$$S_{dia} = DS_nD^{-1} \tag{29}$$

The resulting matrix S_{dia} only has values on its diagonal and we say that we have shifted the basis of the system to align with the eigenvectors of the system. Because our basis is spanned by the aspects contained within resources, our eigenvectors are *eigenresources* of the system and we define these as:

Eigenresources are sets of linearly independent semiotic resources that span all the aspects of the DRAs.

Expressed using learning language, this means that we have shifted to a basis of resources instead of aspects. Because we have already defined a resource to be a linear combination of aspects in Eq. 1, we know that we may construct a basis of resources that capture the aspects of the situation. This new matrix S_{dia} describes the resources of the situation, or at least a mathematical description of what each resource should afford for this situation. It should be noted that not all matrices can be diagonalized. A matrix can only be diagonalized if the matrix D can be constructed. D is called the 'change of basis'-matrix.

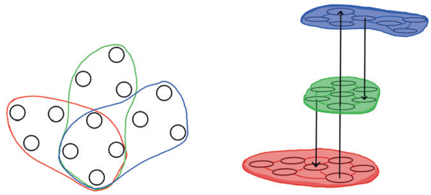
This description is best used when applied to disciplinary RS of the situation. By diagonalising the disciplines's RS, we obtain a set of resources that provides a good balance of aspects for the specific situation. By breaking down the learning goal for the situation into DRAs and identifying aspects with each of them we may construct an ideal 'RS'-matrix that we wish the student's RS to evolve into. The ideal matrix can then be diagonalised to obtain a set of ideal resources. Based on the ideal resources, a lecturer may choose a set of real resources that attempts to match the ideal resources. We extract the subset matrix that represents the DRAs and diagonalizes it.

$$B_n = D \begin{pmatrix} B_{22} & B_{32} \\ B_{23} & B_{33} \end{pmatrix} D^{-1} = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix} \qquad (30)$$

The diagonal values are the eigenvalues of the matrix and thus the eigenvalues of the DRAs of the discipline. For each eigenvalue we also have an eigenresource:

$$B_n \left|R\right\rangle = \lambda_i \left|R_i\right\rangle \qquad (31)$$

where we can match each eigenvalue λ_n to an eigenresource $|R_n\rangle$. The eigenresources themselves may share the same aspects and overlap. By having overlapping aspects, the resources provide opportunities for translation or transduction between different resources. A transduction preserves one aspect from a resource to another, such as representing velocity as a formula and then representing it in a graph. The overlapping aspect for these resources is 'velocity'. To be able to preserve the semiotic material between resources, the initial and the final resource must afford the discernment of the material. If they do not, then there is no way of discerning the semiotic material in the final resource. In FIG. 12 the eigenresources of a situation are represented as different colored areas. A single aspect may be located in several of the resources. Within each resource, the student may move between each aspect but to move between different resources requires an aspect that can be found it both resources.



(a) (b)

FIG. 12: a) The eigenresources of the situation. The eigenresources span the aspects of the situation. b) Within each resource, the student may move between each aspect is affords. To move between different resources, as shown by the arrows, the resources must share aspects to allow for the translation of the semiotic material.

Note that in real-world situations, the resources are often constructed in the moment by the lecturer or by the students as they draw graphs or solve equations. By interacting with the resources, the lecturer/student operate upon them and change the affordances of the resources themselves. The description and representation described above and in FIG. 12 should then be understood then as a snapshot of a learning situation, and one that is constantly evolving.

VII. CONCLUSION

Using the new and novel mathematical description of semiotic resources presented in this article, we have shown how it is possible to model different phenomena that occur in learning situations. Using weighted discernible aspects, we have illustratively constructed different semiotic resources and defined what the concept of affordances [4, 24, 43] would translate into for our model. In so doing, we have shown how it is possible to identify the the disciplinary relevant aspects as the learning goals, and shown how a well designed learning situation will effectively use semiotic resources insightfully, $|R\rangle$, that matches the learning goals, $\langle L|$.

$$\langle L|R\rangle = k \qquad (32)$$

Here, the bra-ket notation of Paul Dirac [27] provides us with an already established notation of the mathematical structure that is well known within the physics discipline.

We then went on to describe the dynamics of the semiotic resources using operators and how the operators change the discernibility of different aspects. The student operator and its expectation value are central parts of all learning; it describes how the student interacts with the semiotic resource and how the students' discerned aspects matches the learning goal.

The order of operators are important and we proposed that it is possible to model and optimize learning situations as a series of operators that are either combined with the student operator or changes the semiotic resource. For example, by changing the order of different activities, such as in the Flipped Classroom case, it becomes possible to start to optimize the learning situation.

In any given learning situation, the student will discern a number of aspects and move between them as they engage with the task. This movement between aspects is modeled as a Markov-chain with the constraint that it ends up in an oscillating state where the student moves between a subset of available discernible aspects. This is the students relevance structure [19, 29], see FIG. 7 and 8. We may also call this Markov-chain the *enacted relevance structure* as explored by Euler *et al* [57].

Using interventions one can help students discern more aspects that lie outside of their RS but within the DRAs of the situation. Interventions are modeled as additions to the Markov-matrix that connects aspects in the DRA to aspects the students discern, as seen in FIG. 9.

A single 'real-life' semiotic resource, such as graph or formula, will have some discernible aspects that the student can move between. However, if the student is to move between different semiotic resources, they should be able to do so using an aspect that both semiotic resources have in their common affordance. See FIG. 12 where movement within a semiotic resource is easy, but movement between them should happen where they overlap.

The DRA-matrix, that describes the DRA of a given situation, may be diagonalizable to shift the basis from aspects to resources. This produces a set of eigenresources that collectively captures the full range of DRAs for a given learning goal. If the eigenresources exists, it then arguably becomes theoretically possible to identify a set of semiotic resources that match the disciplinary RS for the learning goal.

A. On Semiotic Systems

Much of work in social semiotics [4, 21, 35] can be seen to be about the description and use of semiotic systems. A semiotic system is a qualitatively different way of communicating/representing something. However, in the mathematical description we have found no use of this construct and have made the observation that semiotic systems is a higher level construct that may appear later when we begin classifying different ways of using semiotic resources. We suspect that semiotic systems can be found when we group different operators together, such as identifying transient and persistent operators. The operator described in FIG. 4 would be a transient operator because its effect fades with time, whereas the operator in FIG. 1 is a persistent operator.

B. Limitations

1. *The measurement problem*

The limitation with this model is that we can not actually measure the weights of discernible aspects directly, it must be done indirectly using examinations and tests. No classroom is a laboratory with perfect control of all students and what they interact with, so all measurements will be influenced by things not covered in the model.

2. *Toy model*

The framework presented in this paper is a toy model [26] that we designed to answer the question: "How do we compare different semiotic resources?". At this stage it should not be taken as a fully comprehensive description of the very complex phenomenon we call learning. To do this, one will need to incorporate all other known, and unknown aspects, such as, but not limited to: cognition, identity, and socio-economic factors.

In this article, we limited ourselves to the physics education context. This is because we, the authors, are physics education researchers and have the disciplinary knowledge to identify DRAs and student's RS. If a researcher in another area of education would like to apply it in their own educational setting, they must be able to identify DRAs of that specific discipline. The identification of DRAs requires both disciplinary knowledge, but also knowledge within that specific disciplinary education research field.

VIII. IMPLICATION

In [10] Airey & Linder introduces the *collective disciplinary affordance* which aims to capture all the disciplinary affordances that are afforded by all the different semiotic resources and semiotic systems encapsulated by the *Multifacted way of knowing*. The way to apply this in the classroom is to use a multimodal approach to the teaching method. However, it does not describe how the different semiotic systems or semiotic resources should be used, or how they fit together. A teacher knows that they should employ a multimodal approach to their teaching, but does not know how to go about it. It is envisioned that the new framework described in this paper will provide some insight in how different semiotic resources may relate to each other and how they may be used in a learning situation.

A. Finding the narrative

By using the same aspect found in different resources as a means to preserve student discernment when moving between the different resources a teacher may ensure that their narrative is easier to follow. In FIG. 12 we see an example of a situation divided up into three semiotic resources and the potential movement between the semiotic resources. Thus, for any learning situation, a teacher must first identify the learning goals and choose appropriate semiotic resources that affords discernment of DRAs. However, the teacher should also make sure that the order they use the semiotic resources allows for a continuous discernment of aspects. We call the process of identifying what semiotic resources to use, and in what order, as finding the narrative.

IX. ACKNOWLEDGMENT

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Appendix: Working definitions of Concepts

Below is a description of concepts from Social Semiotics and Variation Theory of Learning, and a description of how they are manifested in the mathematical model.

Term	PER usage	Mathematical description
Aspect	"A particular part or feature of a situation, an idea, a problem, etc.; a way in which it may be considered"[13] which includes quantities, shapes, relationships and dynamic effects	What may be discerned in a given system, also known as Discernible Aspect
Disciplinary Relevant Aspects (DRA)	The aspects a discipline finds relevant for a specific situation, idea or problem	What the discipline wants students to discern/learn in a given system, also known as the Learning Goals
Semiotic Resource (SR)	The resources used within a discipline to communicate or make meaning.	A collection of discernible aspects. such as a graph or a formula
Disciplinary Discernment (DD)	to notice and think about in ways that lead to meaning-making with regards to DRAs	to notice and think about in ways that lead to meaning-making with regards to DRAs
Relevance Structure (RS)	What the student finds relevant with regards to a specific situation, idea, or problem.	The stable Markov-chain of a students discernment chain in a given situation
Affordance	What a situation affords to an agent.	How well an aspect may be discerned in a given system, a weighted discernible aspect

Appendix: Consent Forms

Pre-GDPR

Before the GDPR was enacted, the participants signed the following consent form before participating in the study. This consent form was rewritten when GDPR was enacted and the updated consent form can be seen further below.

Papers I and II

För godkännande av medverkan I intervjuer och filmklipp för projektet ”Programmering som ett verktyg för lärande i fysik” vid NRCF (Nationellt Resurscentrum för Fysik) vid Lunds Universitet.

I samband med detta projekt gäller följande:

- Ljud och filmupptagning kommer att förekomma.
- Anonyma citat kan komma att användas för publikationer och presentationer.
- Om inspelningarna blir aktuella att användas i andra forskningsprojekt utöver ”Programmering som ett verktyg för lärande i fysik”, kommer ni bli kontaktade för nytt samtycke.
- Filmerna kommer förvaras och behandlas lokalt på NRCF och inte distribueras utanför forskargruppen.
    - Forskargruppen består av alla involverade i projektet ”Programmering som ett verktyg för lärande i fysik”:
        - Kim Svensson, Lunds Universitet, NRCF
        - Moa Eriksson, Lunds Universitet, Uppsala Universitet, NRCF
        - Ann-Marie Pendrill, Lunds Universitet, NRCF
        - Urban Eriksson, Lunds Universitet, NRCF
        - Lassana Ouattara, Lunds Universitet, NRCF
    - Filmer och ljudfiler kommer förvaras enligt offentlighetsprincipen och gallras efterhand.
    - Individer kan när som helst gå ur studien genom att meddela Kim Svensson, då förstörs allt material som berör individen.
        - resurscentrum@fysik.lu.se

Härmed godkänner jag (markera allt som gäller)

☐ att intervjuer och filmer får användas i forskningsprojektet och att material kan studeras av alla i forskargruppen.

☐ att anonyma citat och/eller bilder kan användas anonymt i publikationer.

☐ att jag kommer bli filmad under studien.

☐ att jag kan bli kontaktad om insamlat material kan användas till ett annat forskarprojekt.

e-post:____

Telefon:____

Kontakt: resurscentrum@fysik.lu.se

Datum:_________________________

Underskrift:____

Namnförtydligande:____

Efter att materialet har samlas in, kryssa i följande ruta för att visa att du har förstått ovanstående.

☐ Jag förstår ovantstående och förstår innebörden av och varför materialet samlas in.

Post-GDPR

The consent form for papers I and II were out of date at the end of the data-collection and a new consent form was constructed. The participants did not have to consent again, but the data handling and the data storage must follow the guidelines used in the new consent form.

Papers I and II

Informed Consent – Information Sheet

National Resource Centre for Physics Education, Lund University

Project: *"Programming as a means for meaning-making in physics education."*

PARTICIPANT INFORMATION SHEET

You are being invited to take part in research on what programming offers in the area of Physics and Astronomy Education Research (PAER).

Kim Svensson, PhD student at the National Resource Centre for Physics Education (NRCF), Lund University, is leading this research.

Before you decide to take part in this study, it is important that you understand the why the research is being conducted and how it will be done as well as your part in this research.

Please take time to read the following information carefully.

What is the purpose of the study?

The purpose of this study is to examine what text-based in the Processing environment with the programming language Python, offers the student with respect the areas of meaning making and understanding with respect to physics and physics exploration. The research aims to observe what the combination of Coding, Visualization and Interaction contributes to the meaning-making and understanding with respect to the physics discipline.

- Interaction: Mouse and keyboard real-time interactions with simulations.
- Visualization: Creating representations of abstract models on screen.
- Coding: Implementing models and running the code.

The study also aims to find out at what programming proficiency level is needed to extract disciplinary meaning.

The data collected in this study will be in the form of video and audio recordings, forms and questionnaires. The research team will look at how You communicate when in a physics/programming environment with your peers. In the individual and group interviews the research team will examine Your answers to questions about the study and programming as a tool to be used in physics education.

Why have I been chosen to take part?

You are invited to participate in this study because you volunteered to take part in this study.

What are the benefits of taking part?

By sharing your experiences with us, you will be helping Kim Svensson and the research team at NRCF, Ann-Marie Pendrill, Urban Eriksson, Lassana Ouattara, Moa Eriksson, and Lund University to better understand what programming offers for meaning-making and understanding with respect to the physics discipline.

Are there any risks associated with taking part?

There are no significant risks associated with participation in this study.

Do I have to take part?

No, taking part is entirely voluntary. If you decide to take part, please keep this Information Sheet and complete the Informed Consent Form to show that you understand your rights in relation to the research and that you are happy to take part in this study.

You are free to withdraw your information from the project data set at any time before the data is destroyed or fully anonymised. The data will be destroyed during the *fall of 2020* when this project ends. The data will be weeded before this date. The date for anonymization cannot be set as it depends on the analysis process but will happen before or on the date of the destruction of the data.

You should note that your data may be used in the production of formal research outputs (e.g. journal articles, conference papers, theses and reports) prior to the destruction or anonymization of the data. You are advised to contact the lead researcher, or the NRCF, at the earliest opportunity should you wish to withdraw from the study.

To withdraw from the study, please contact the lead researcher or the NRCF using any of the following information channels and they will comply with you request as soon as possible. Please be as clear as possible with your request.

Lead Researcher
Email: Kim.Svensson@fysik.lu.se
Blog: https://nrcf-programming.blogg.lu.se/

NRCF
Email: resurscentrum@fysik.lu.se
Web: http://www.fysik.org/

You do not need to give a reason. A decision to withdraw, or not to take part, will not affect you in any way.

What will happen if I decide to take part?

During the study you will participate in five sessions designed to highlight different aspects of programming with respect to meaning-making and understanding physics. Each session will be two hours long.

Each session will be video and audio recorded with multiple cameras and microphones. During the sessions you will be asked questions about your physics and/or programming knowledge.

Your personal data: first name, last name, email address, phone number, age and educational background will be collected and used in the study.

You will need to provide your consent to us with respect to these information gathering methods:

- video recording
- audio recording
- forms and questionnaires
- individual interviews

- group interviews.

In total, the study is expected to take approximately ten hours, spread out over five separate sessions spread over two months.

Data Protection and Confidentiality

Your data will be processed in accordance with the General Data Protection Regulation (GDPR) (EU) 2016/679 (GDPR). All information collected about you will be kept strictly confidential. Unless they are anonymized in our records, your data will be referred to by a unique participant number rather than by name. If you consent to all the above methods of information gathering, all recordings will be destroyed during the *fall of 2020.* Your data will only be viewed by the lead researcher and the research team at NRCF which have been named earlier. All electronic data will be stored on an external Solid-State Drive, kept in a locked drawer in the NRCF locales. All the paper records will be stored in a locked drawer in the NRCF locales. Your consent information will be kept separate from your responses in order to minimise the risk in the event of data breach. The lead researcher will take responsibility for data destruction and all collected data will be destroyed on or before *fall of 2020.*

What will happen with the results of this study?

The results of this study may be summarised in published articles, reports and presentations. Quotes or key findings will always be made anonymous in any formal outputs.

Making a Complaint

If you are unhappy with any aspect of this research, please first contact the lead researcher, see above for contact details. If you still have concerns and wish to make a formal complaint, please write to the NRCF, see above for contact details.

In your letter please provide information about the research project, specify the name of the researcher and detail the nature of your complaint.

Data Protection Rights

Information classification (2,1,1) (Confidentiality, Accuracy, Accessibility)

Lund University processes personal data in order to fulfil its task as a public authority and university.

The University's task is to provide research and education, collaborate with society, communicate its activities and enable the utilisation of research results produced at the University.

All processing of personal data within the University is conducted in order to carry out these tasks. Only personal data required for these purposes will be processed.

Lund University (Corporate identity number 202100-3211) is the data controller for such processing of personal data for which the University has a set purpose and means.

Contact information for the controller of personal data:

dataskyddsombud@lu.se

Box 117, 221 00 Lund, Sweden
Telephone +46 (0)46 222 0000 (switchboard)
Fax +46 (0)46 222 4720

Invoice address: Box 188, 221 00 Lund
Organisation number: 202100-3211

Anyone who believes that Lund University has processed his or her personal data contrary to the Data Protection Act and related supplementary national legislation has the right to **submit complaints to the Swedish Data Inspection Board**.

Informed Consent – Consent Form

National Resource Centre for Physics Education, Lund University

Project: *“Programming as a means for meaning-making in physics education.”*

This is a consent form to acknowledge the information sheet and participation in research at NRCF at Lund University.

- I have read the information sheet and understands:
  - ☐ The purpose of the study.
  - The information that will be gathered and approves the gathering of information with the following methods:
    - ☐ Video recording.
    - ☐ Audio recording.
    - ☐ Forms and Questionnaires.
    - ☐ Individual Interviews.
    - ☐ Group Interviews.
  - My right to:
    - ☐ Withdraw my consent/participation at any time.
    - ☐ Access the data collected about myself.
- I approve that the information gathered:
  - ☐ Will be used in research reports (e.g. journal articles, conference papers, theses and reports).
  - ☐ Will be analysed by the lead researcher and the research team at NRCF.
  - Consists of:
    - ☐ First name, last name, phone number, email address, age and educational background.

Informed Consent – Consent Form

National Resource Centre for Physics Education, Lund University

Project: *“Programming as a means for meaning-making in physics education.”*

This is a consent form to acknowledge the information sheet and participation in research at NRCF at Lund University.

NAME:____

EMAIL:____

PHONE NUMBER:____

SIGNATURE:____

To contact the lead researcher or the research team performing this study please use the following information:

Lead researcher
Email: Kim.Svensson@fysik.lu.se
Blog: https://nrcf-programming.blogg.lu.se/

NRCF (research team)
Email: resurscentrum@fysik.lu.se
Web: http://www.fysik.org/

Teacher perspective

The consent form and information sheet below refers to a data collection with teachers. However, this project has been delayed and the data has not been analysed and no results published.

Informed Consent – Information Sheet

National Resource Centre for Physics Education, Lund University

Project: *"Programming as a means for meaning-making in physics education."*

Teacher part.

PARTICIPANT INFORMATION SHEET

You are being invited to take part in research on what programming offers in the area of Physics and Astronomy Education Research (PAER).

Kim Svensson, PhD student at the National Resource Centre for Physics Education (NRCF), Lund University, is leading this research.

Before you decide to take part in this study, it is important that you understand the why the research is being conducted and how it will be done as well as your part in this research.

Please take time to read the following information carefully.

What is the purpose of the study?

The purpose of this study is to examine what text-based in the Processing environment with the programming language Python, offers the student with respect the areas of meaning making and understanding with respect to physics and physics exploration. The research aims to observe what the combination of Coding, Visualisation and Interaction contributes to the meaning-making and understanding with respect to the physics discipline.

- Interaction: Mouse and keyboard real-time interactions with simulations.
- Visualisation: Creating representations of abstract models on screen.
- Coding: Implementing models and running the code.

The study also aims to find out at what programming proficiency level is needed to extract disciplinary meaning.

The data collected in this study will be in the form of video and audio recordings, forms and questionnaires, online comments and discussions. In the individual and group interviews the research team will examine Your answers to questions about the study and programming as a tool to be used in physics education.

Why have I been chosen to take part?

You are invited to participate in this study because you volunteered to take part in this study.

What are the benefits of taking part?

By sharing your experiences with us, you will be helping Kim Svensson and the research team at NRCF, Ann-Marie Pendrill, Urban Eriksson, Lassana Ouattara, Moa Eriksson, and Lund University to better understand what programming offers for meaning-making and understanding with respect to the physics discipline.

Are there any risks associated with taking part?

There are no significant risks associated with participation in this study.

Do I have to take part?

No, taking part is entirely voluntary. If you decide to take part, please keep this Information Sheet and complete the Informed Consent Form to show that you understand your rights in relation to the research and that you are happy to take part in this study.

You are free to withdraw your information from the project data set at any time before the data is destroyed or fully anonymised. The data will be destroyed during the *fall of 2022* when this project ends. The data will be weeded before this date. The date for anonymisation cannot be set as it depends on the analysis process but will happen before or on the date of the destruction of the data.

You should note that your data may be used in the production of formal research outputs (e.g. journal articles, conference papers, theses and reports) prior to the destruction or anonymisation of the data. You are advised to contact the lead researcher, or the NRCF, at the earliest opportunity should you wish to withdraw from the study.

To withdraw from the study, please contact the lead researcher or the NRCF using any of the following information channels and they will comply with you request as soon as possible. Please be as clear as possible with your request.

Lead Researcher
Email: Kim.Svensson@fysik.lu.se
Blog: https://nrcf-programming.blogg.lu.se/

NRCF
Email: resurscentrum@fysik.lu.se
Web: http://www.fysik.org/

You do not need to give a reason. A decision to withdraw, or not to take part, will not affect you in any way.

What will happen if I decide to take part?

During the study you will participate in online activities and discussions, the comments and discussions pertaining to programming, physics or physics education will be collected and studied as part of the research project.

You will also participate in two mini conferences during the study, they are part of the examination of the course. During these two mini conferences you will present two different projects. These presentations will be audio and video recorded for analysis.

Your personal data: first name, last name, email address, age and educational background will be collected and used in the study.

During the mini-conference and throughout the study, there will be opportunity to partake in individual interviews and/our group interviews/discussion sessions. These will be audio and video recorded for analysis.

You will need to provide your consent to us with respect to these information gathering methods:

- video recording
- audio recording
- forms and questionnaires
- individual interviews
- group interviews.

Data Protection and Confidentiality

Your data will be processed in accordance with the General Data Protection Regulation (GDPR) (EU) 2016/679 (GDPR). All information collected about you will be kept strictly confidential. Unless they are anonymized in our records, your data will be referred to by a unique participant number rather than by name. If you consent to all the above methods of information gathering, all recordings will be destroyed during the *fall of 2022.* Your data will only be viewed by the lead researcher and the research team at NRCF which have been named earlier. All electronic data will be stored on an external Solid-State Drive, kept in a locked drawer in the NRCF locales, with no connection to the internet. All the paper records will be stored in a locked drawer in the NRCF locales. Your consent information will be kept separate from your responses in order to minimise the risk in the event of data breach. The lead researcher will take responsibility for data destruction and all collected data will be destroyed on or before *fall of 2022.*

What will happen with the results of this study?

The results of this study may be summarised in published articles, reports and presentations. Quotes or key findings will always be made anonymous in any formal outputs.

Making a Complaint

If you are unhappy with any aspect of this research, please first contact the lead researcher, see above for contact details. If you still have concerns and wish to make a formal complaint, please write to the NRCF, see above for contact details.

In your letter please provide information about the research project, specify the name of the researcher and detail the nature of your complaint.

Data Protection Rights

Information classification (2,1,1) (Confidentiality, Accuracy, Accessibility)

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Invoice address: Box 188, 221 00 Lund
Organisation number: 202100-3211

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Informed Consent – Consent Form

National Resource Centre for Physics Education, Lund University

Project: *“Programming as a means for meaning-making in physics education.”*

This is a consent form to acknowledge the information sheet and participation in research at NRCF at Lund University.

- I have read the information sheet and understands:

    ☐ The purpose of the study.

    - The information that will be gathered and approves the gathering of information with the following methods:

        ☐ Online discussions and comments.

        ☐ Video recording.

        ☐ Audio recording.

        ☐ Forms and Questionnaires.

        ☐ Individual Interviews.

        ☐ Group Interviews.

    - My right to:

        ☐ Withdraw my consent/participation at any time.

        ☐ Access the data collected about myself.

- I approve that the information gathered:

    ☐ Will be used in research reports (e.g. journal articles, conference papers, theses and reports).

    ☐ Will be analysed by the lead researcher and the research team at NRCF.

    - Consists of:

        ☐ First name, last name, email address, age and educational background.

Informed Consent – Consent Form

National Resource Centre for Physics Education, Lund University

Project: *"Programming as a means for meaning-making in physics education."*

Teacher part.

This is a consent form to acknowledge the information sheet and participation in research at NRCF at Lund University.

NAME:____

EMAIL:____

PHONE NUMBER:____

SIGNATURE:____

To contact the lead researcher or the research team performing this study please use the following information:

Lead researcher
Email: Kim.Svensson@fysik.lu.se
Blog: https://nrcf-programming.blogg.lu.se/

NRCF (research team)
Email: resurscentrum@fysik.lu.se
Web: http://www.fysik.org/

Papers IV, V, and VI

The consent was collected using a Microsoft Forms sheet. Within the sheet was a link to a PDF version of the information sheet, as well as a docx version of the information sheet for the participants to download. First the PDF version of the information sheet will be presented and then the Microsoft Forms version of the information sheet. The student could only sign online through the Microsoft Forms version. Note, the PDF-download of the Microsoft Forms has some layout errors due to Microsoft's internal process, which is why a separate PDF version of the information sheet exists.

Informed Consent – Information Sheet

LUND UNIVERSITY

FACULTY OF SCIENCE

Date 2020-02-15

The National Resource Centre for Physics Education and Lund University Physics Education Research group, Lund University.

Project: *"Constructing Semiotic Resources using Social Semiotics and Variation Theory for use in physics education"*

PARTICIPANT INFORMATION SHEET

You are being invited to take part in the study entitled "Constructing Semiotic Resources using Social Semiotics and Variation Theory for use in physics education" focusing on the development and testing of theoretical frameworks used to analyse teaching and learning of physics.

Ph. Lic. Kim Svensson, a PhD student in Lund University Physics Education Research (LUPER) group, is leading this research project, together with associate professor Urban Eriksson, director of the National Resource Centre for Physics Education (NRCF) and scientific leader of the LUPER group.

Before you decide to take part, it is important that you understand why the research is being conducted and what it will involve.

Please take time to read the following information carefully.

What is the purpose of the study?

The purpose of this study is twofold. The first is to develop a completely new particular representation to be used for enhancing the learning of physics. The second is to investigate the application and usefulness of this representation in physics teaching and learning. The results from the study will help to further develop the theories and the construction of new representations for use in physics education.

Why have I been chosen to take part?

You are invited to participate in this study because you are enrolled in a course dealing with thermodynamics.

What are the benefits of taking part?

By participating, you will be helping the research team at LUPER to better understand certain methodological issues related to physics education and how carefully chosen representations may enhance the learning of physics.

Are there any risks associated with taking part?

There are no specific risks associated with participation in this study.

Do I have to take part?

No, taking part is entirely voluntary. If you decide to take part, please keep this information which will be provided to you also by e-mail and declare your consent in regard to this study at the bottom of this form to show that you understand your rights in relation to the research and that you are happy to take part in this study.

You are free to withdraw your information from the project data set at any time before the raw data is destroyed or fully anonymised. The raw data will be archived during the fall of 2023 at the latest. The data will be weeded before this date. If you withdraw from the study your raw data will be destroyed. You are advised to contact the lead researchers, or the LUPER group, at the earliest opportunity should you wish to withdraw from the study.

You should note that your data may be used in the production of formal research outputs (e.g. journal articles, conference papers, theses, reports, and datasets) prior to the destruction of the data.

To withdraw from the study, please contact the lead researcher Kim Svensson (kim.svensson@fysik.lu.se). You can also contact Urban Eriksson (urban.eriksson@fysik.lu.se) should the lead researcher be absent so that your request can be dealt with as soon as possible. Please be as clear as possible with your request.

You do not need to give a reason to withdraw. A decision to withdraw, or not to take part, will not affect you in any way.

What will happen if I decide to take part?

You will be observed during your participation in a group interview over Zoom with your peers. The interview will be audio and video recorded, and the notes and/or figures produced will be documented for further analysis. Please note that since the data includes videos you could be identified in the data until it gets completely anonymised. Thus, should you not give consent to have your face recorded you can choose to participate using only audio.

Data Protection and Confidentiality

If you consent to participate in this study, your data will be processed in accordance with the General Data Protection Regulation (GDPR) (EU) 2016/679 (GDPR). All information collected about you will be kept strictly confidential. Unless they are anonymized in our records, your data will be referred to by a unique participant number rather than by name. If you consent to all the above methods of information gathering, all recordings will be destroyed during the fall of 2023 at the latest.

Your data will only be viewed by the lead researcher and the research team as specified earlier.

All electronic data will be stored on an external Solid-State Drive, kept in a locked safe belonging to the LUPER group. Your consent information will be kept separate from your responses in order to minimise the risk in the event of data breach. The lead researcher will take responsibility for data destruction and all collected data will be destroyed on or before fall of 2023.

What will happen with the results of this study?

The results of this study may be summarised in published articles, reports and presentations. All reference to raw data will have been anonymized in any formal outputs as guaranteed earlier.

Making a Complaint

If you are unhappy with any aspect of this research, please first contact the lead researcher, see above for contact details. If you still have concerns and wish to make a formal complaint, please contact Urban Eriksson using the contact information given earlier.

In your letter please provide information about the research project, specify the name of the researcher and detail the nature of your complaint.

Data Protection Rights

Information classification (2,1,1) (Confidentiality, Accuracy, Accessibility)

Lund University processes personal data in order to fulfil its task as a public authority and university.

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Invoice address: Box 188, 221 00 Lund
Organisation number: 202100-3211

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Informed Consent: Spring 2021 - Constructing Representations for Physics

PARTICIPANT INFORMATION SHEET

You are being invited to take part in the study entitled "Constructing Semiotic Resources using Social Semiotics and Variation Theory for use in physics education" focusing on the development and testing of theoretical frameworks used to analyse teaching and learning of physics.

Ph. Lic. Kim Svensson, a PhD student in Lund University Physics Education Research (LUPER) group, is leading this research project, together with associate professor Urban Eriksson, director of the National Resource Centre for Physics Education (NRCF) and scientific leader of the LUPER group.

Before you decide to take part, it is important that you understand why the research is being conducted and what it will involve.

Please take time to read the following information carefully.

The information sheet should be downloaded for future reference:

PDF: https://drive.google.com/uc?export=download&id=1f4gAbk_ThrULgDdJN9wm3HLDhGkqR6kX

DOCX: https://drive.google.com/uc?export=download&id=1ubhM_9FC65_eYUp1DUCa22JN-OklWQ53

* Obligatoriskt

1. What is the purpose of the study?

   The purpose of this study is twofold. The first is to develop a completely new particular representation to be used for enhancing the learning of physics. The second is to investigate the application and usefulness of this representation in physics teaching and learning. The results from the study will help to further develop the theories and the construction of new representations for use in physics education. *

   ○ I have read and understood the text above

2. Why have I been chosen to take part?

You are invited to participate in this study because you are enrolled in a course dealing with thermodynamics. *

◯ I have read and understood the text above

3. What are the benefits of taking part?

By participating, you will be helping the research team at LUPER to better understand certain methodological issues related to physics education and how carefully chosen representations may enhance the learning of physics. *

◯ I have read and understood the text above

4. Are there any risks associated with taking part?

There are no specific risks associated with participation in this study. *

◯ I have read and understood the text above

5. Do I have to take part?

No, taking part is entirely voluntary. If you decide to take part, please keep this information which will be provided to you also by e-mail and declare your consent in regard to this study at the bottom of this form to show that you understand your rights in relation to the research and that you are happy to take part in this study.

You are free to withdraw your information from the project data set at any time before the raw data is destroyed or fully anonymised. The raw data will be archived during the fall of 2023 at the latest. The data will be weeded before this date. If you withdraw from the study your raw data will be destroyed. You are advised to contact the lead researchers, or the LUPER group, at the earliest opportunity should you wish to withdraw from the study.

You should note that your data may be used in the production of formal research outputs (e.g. journal articles, conference papers, theses, reports, and datasets) prior to the destruction of the data.

To withdraw from the study, please contact the lead researcher Kim Svensson (kim.svensson@fysik.lu.se). You can also contact Urban Eriksson (urban.eriksson@fysik.lu.se) should the lead researcher be absent so that your request can be dealt with as soon as possible. Please be as clear as possible with your request.

You do not need to give a reason to withdraw. A decision to withdraw, or not to take part, will not affect you in any way. *

○ I have read and understood the text above

6. What will happen if I decide to take part?

You will be observed during your participation in a group interview over Zoom with your peers. The interview will be audio and video recorded, and the notes and/or figures produced will be documented for further analysis. Please note that since the data includes videos you could be identified in the data until it gets completely anonymised. Thus, should you not give consent to have your face recorded you can choose to participate using only audio. *

○ I have read and understood the text above

7. Data Protection and Confidentiality

If you consent to participate in this study, your data will be processed in accordance with the General Data Protection Regulation (GDPR) (EU) 2016/679 (GDPR). All information collected about you will be kept strictly confidential. Unless they are anonymized in our records, your data will be referred to by a unique participant number rather than by name. If you consent to all the above methods of information gathering, all recordings will be destroyed during the fall of 2023 at the latest.

Your data will only be viewed by the lead researcher and the research team as specified earlier.

All electronic data will be stored on an external Solid-State Drive, kept in a locked safe belonging to the LUPER group. Your consent information will be kept separate from your responses in order to minimise the risk in the event of data breach. The lead researcher will take responsibility for data destruction and all collected data will be destroyed on or before fall of 2023. *

◯ I have read and understood the text above

8. What will happen with the results of this study?

The results of this study may be summarised in published articles, reports and presentations. All reference to raw data will have been anonymized in any formal outputs as guaranteed earlier. *

◯ I have read and understood the text above

9. Making a Complaint

If you are unhappy with any aspect of this research, please first contact the lead researcher, see above for contact details. If you still have concerns and wish to make a formal complaint, please contact Urban Eriksson using the contact information given earlier.

In your letter please provide information about the research project, specify the name of the researcher and detail the nature of your complaint. *

◯ I have read and understood the text above

10. Data Protection Rights

Information classification (2,1,1) (Confidentiality, Accuracy, Accessibility)

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◯ I have read and understood the text above

11. Contact information for the controller of personal data:

dataskyddsombud@lu.se
Box 117, 221 00 Lund, Sweden
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Anyone who believes that Lund University has processed his or her personal data contrary to the Data Protection Act and related supplementary national legislation has the right to submit complaints to the Swedish Data Inspection Board. *

◯ I have read and understood the text above

12. Informed Consent 1(2)

Please indicate, by checking all of the appropriate boxes, that you have read and understood the information provided to you about participation in this research. I have read and understood:

☐ the purpose of the study

☐ my right to access the data collected about myself

☐ my right to withdraw my consent/participation at any time and if I do, my data will be destroyed

☐ what type of data will be collected and how this will be performed

☐ that any raw data of which I am part will only be accessed by the researchers specified in the information given above

13. Informed Consent 2(2)

Please indicate, by checking all of the appropriate boxes, the level of consent that you give. I agree:

- [ ] to be video and audio recorded as part of my participation
- [ ] that anonymised data containing transcribed audio recordings from me can be used in scientific publications
- [ ] that anonymised data containing video and/or photographs of me can be used in scientific publications
- [ ] that anonymised data of my can be used to create a dataset which is shared with people from the physics education research community.

14. By providing my name and e-mail address below I hereby agree to participate in this study. *

Please provide both your name and e-mail address so that we will be able to contact you about your participation if needed.

12. Informed Consent 1(2)

Please indicate, by checking all of the appropriate boxes, that you have read and understood the information provided to you about participation in this research.

I have read and understood:

☐ the purpose of the study

☐ my right to access the data collected about myself

☐ my right to withdraw my consent/participation at any time and if I do, my data will be destroyed

☐ what type of data will be collected and how this will be performed

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Please indicate, by checking all of the appropriate boxes, the level of consent that you give.

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☐ to be video and audio recorded as part of my participation

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Please provide both your name and e-mail address so that we will be able to contact you about your participation if needed.

Ange ditt svar

Figure 34: A screenshot of the Microsoft Forms consent form that the participants used to consent to the study and the data handling.

Appendix: Interview Questions

Interview questions for project 1: students

The following questions were asked to the participants of the programming workshop. The questions were asked during the last, fifth, session. The Swedish original questions at the top with the translated English questions at the bottom.

Questions in Swedish

Individual interview questions

Fråga 1

- Vad tycker du om workshopen som ett sätt att lära sig fysik?
- Vad tycker du att du lärde dig under workshopen?
- Vad var bra/dåligt/svårt/lätt?
- Vad tror du man behöver kunna för att utnyttja workshopen till fullo?
  - Mer fysik?
  - Mer programmering?
  - Mer uppgifter?
  - Mer demonstrationer?

Fråga 2

- Kan du förklara “Particle”-klassen?

- Förklara vad de olika funktionerna gör (kortfattat):
  - `__init__()`
  - `show()`
  - `update()`
  - `interact()`
- vad kan dessa användas till?

- Vad är det som programmering ger Dig som Du (kanske) inte kunde gjort på något annat sätt?

Group interview questions

Fråga 1

- Vad tycker ni är fördelarna med programmering jämfört med vanlig undervisning såsom föreläsning i klassrum?
- Vad tycker ni är nackdelarna med programmering?
- Hur vill ni kunna/kan ni använda programmering i fysik?
- Vilken roll har programmering i fysik forskning?

Fråga 2

- Hur skulle ni simulera en galaxkollision?

Questions in English

Individual interview questions

Question 1

- What do you think about the workshop as a way to learn physics?
- What do you think you learned during the workshop?
- What was good/bad/hard/easy?
- What do you think a person needs to know to fully utilise the workshop?
  - More physics?
  - More programming?
  - More exercises?
  - More demonstrations?

Question 2

- Can you explain the Particle-class?
- Explain what the different functions do:
  - `__init__()`
  - `show()`
  - `update()`
  - `interact()`
- What can these be used for?

Question 3

- What is that programming offers You that You (maybe) could not have done in another way?

Group interview questions

Question 1

- What do you think are the advantages with programming compared to normal education like lectures in a classroom?
- What do you think are the disadvantages of programming?
- How can you, or wish to able to, use programming in physics?
- What role does programming have in physics research?

Question 2

- How would you simulate a galaxy-collision?

Interview questions for project 1: teachers

The following questions were asked to teachers that participated in the programming for teachers course that was to expand upon papers I and II. The data from these interviews are still being analysed. The questions are first presented in Swedish, which was the original language, and then translated to English further down. The structure of the questions was designed to follow a semi-structured manner were probing questions could be asked if the initial answer did not provide enough information.

Questions in Swedish

Fråga 1

- Hur går det med Projekt 2?
    - Vad har du gjort/planerar du att göra?
    - Hur tror du att eleverna kommer uppleva det?
        * Är det nytt för dom eller har de gjort liknande innan?

Fråga 2

- Vad måste ändras/förbättras för att du ska kunna använda programmering i fysikundervisningen?
    - Din kunskap?
    - Din skola?
        * Skolverket?
    - Dina elever?

Fråga 3

- Vad ser du för styrkor/svagheter med programmering i fysikundervisning?
    - Svårigheter med:
        * Hårdvara?
        * Mjukvara?
        * IT-systemet?
        * Kollegor?

    * Elever?

  - Skapa egna modeller/lösningar:
    * Förlora kontrollen över lösningarna?
      · Inte ha svar.
    * Utforska lösningar tillsammans?

Fråga 4

- Vilka elever tror du har nytta av programmeringen i fysikundervisning?
  - Vad skulle det ge eleverna?
  - Har några elever överraskat dig?
    * Intresse?
    * Förmåga?

Fråga 5

- Vad tycker du om kursen?
  - Upplägget?
  - Projekten?
  - Mötet i Lund?

Fråga 6

- Vad tycker du om programmering?
  - I allmänhet?
  - I skolan?
  - I fysiken?

Questions in English

Question 1

- What is the status of Project 2?
  - What have you done/what do you plan to do?
  - How do you think the students will take it?
    - * Is it new for them, or have they done something similiar before?

Question 2

- What must change/improve for you to use programming in physics education?
  - Your knowledge?
  - Your school?
    - * The Swedish National Agency for Education?
  - Your students?

Question 3

- What strengths or weaknesses to you see in using programming in physics education?
  - Difficulties with:
    - * Hardware?
    - * Software?
    - * IT-system?
    - * Colleagues?
    - * Students?
  - Creating their own models/solutions:
    - * Losing the control over solutions?
      - · Not having answers.
    - * Explore solutions together?

Question 4

- Which students would benefit from using programming in physics education do you think?

- What would it afford the student?
- Has any student surprised you?
  * Interest?
  * Ability?

Question 5

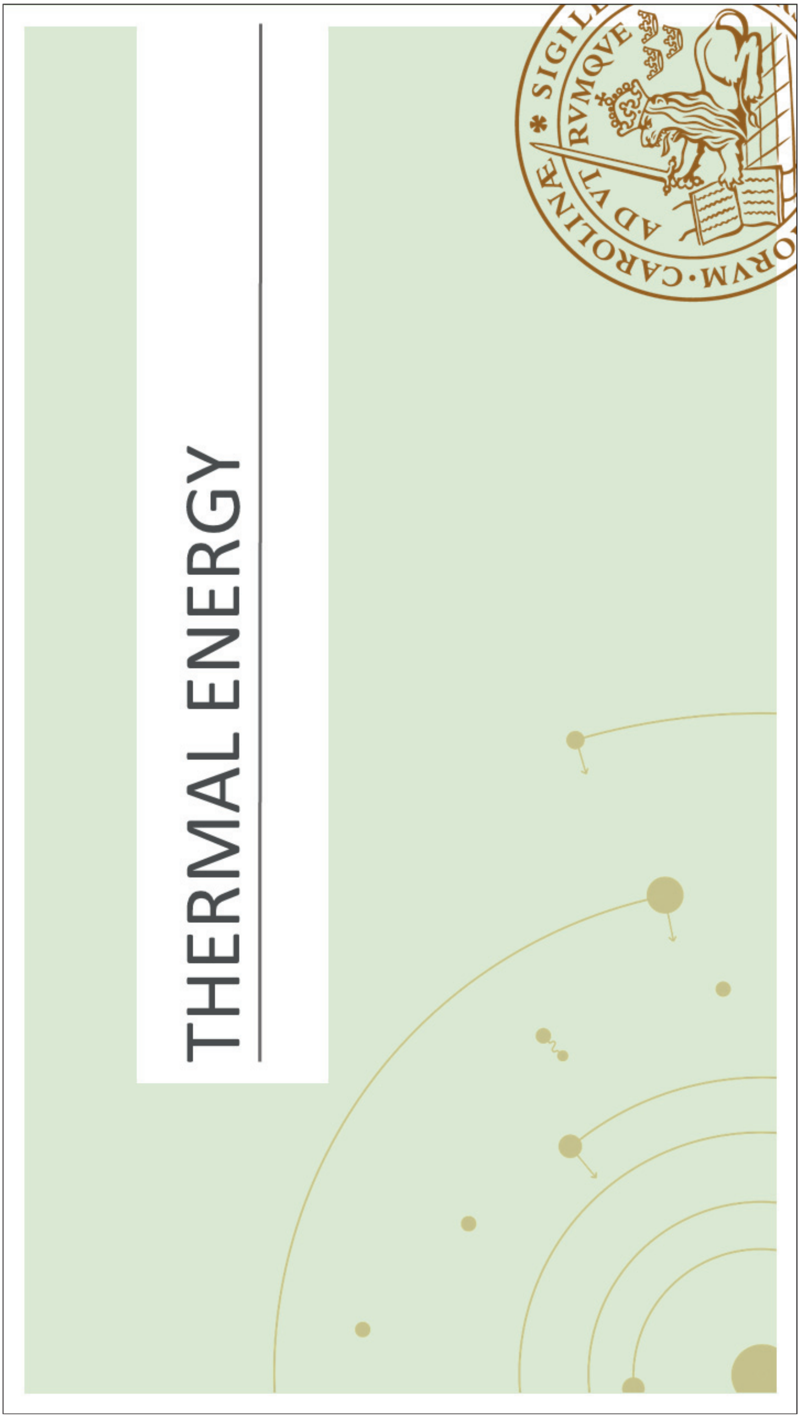
- What do you think about the course?
  - Structure?
  - Projects?
  - The meeting in Lund?

Question 6

- What do you think about programming?
  - In general?
  - In school?
  - In physics?

Interview exercises for project 2

The following PowerPoint was presented to the participants in project 2. The aim was to introduce a new representation to them, have them manipulate it and study how they construct and use representations to convey and construct meaning about physical concepts.


THERMAL ENERGY

How would you describe the concept of Thermal Energy to a classmate?

DRAW HERE

Please use different types of representations: Text, Formulas, Graphs, Sketches

How do you believe that a physicist would describe the concept?

DRAW HERE

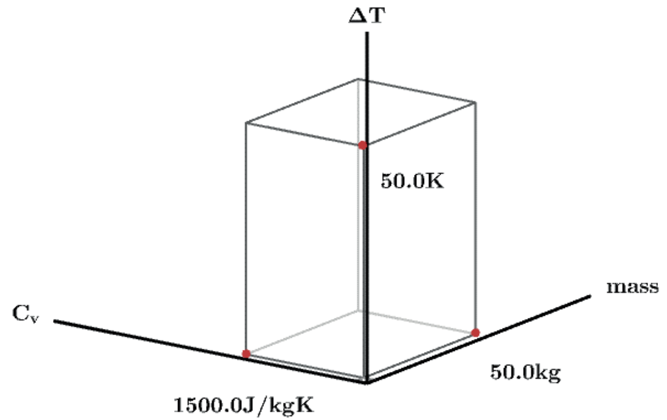
Please use different types of representations: Text, Formulas, Graphs, Sketches

FORMULA

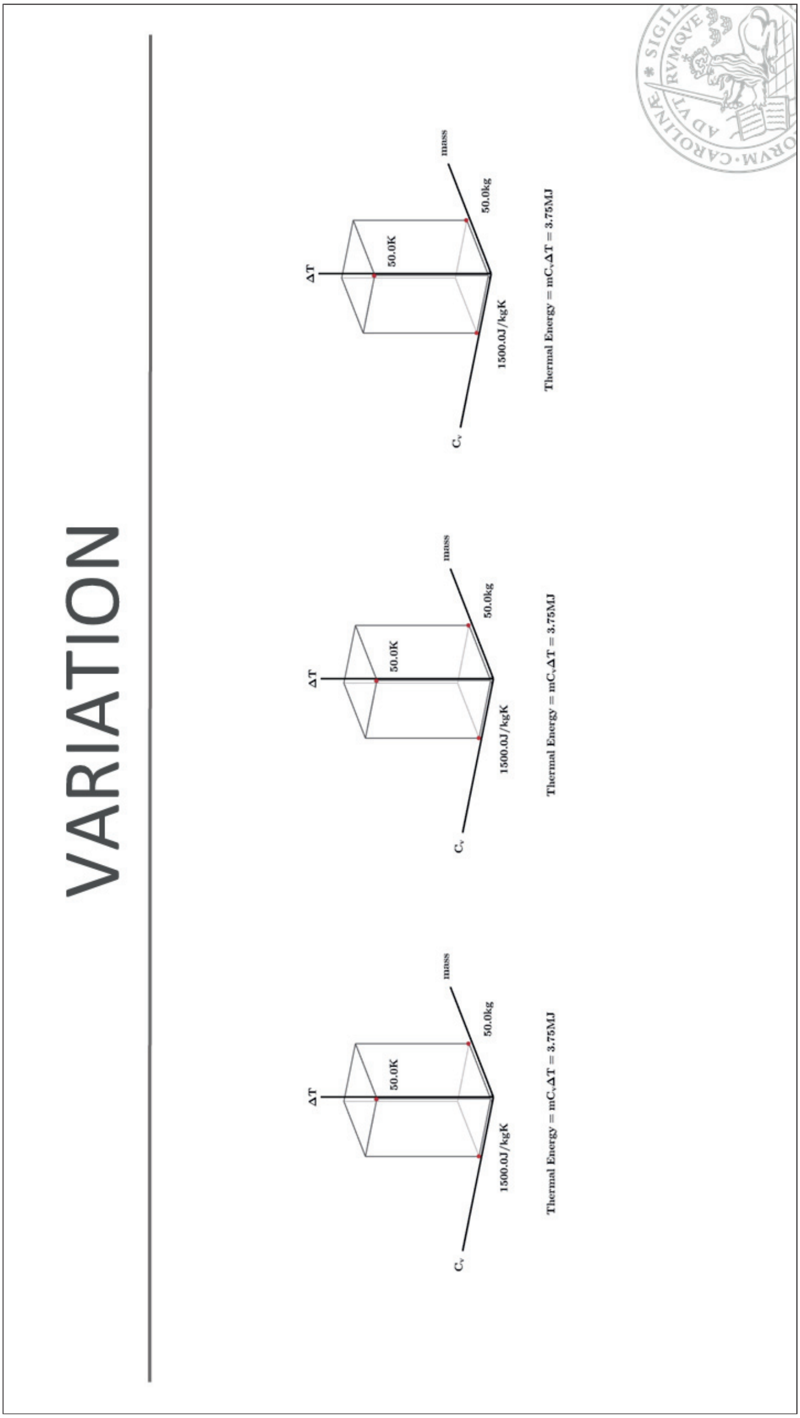
$$\underbrace{E}_{\text{Thermal Energy}} = \overbrace{m}^{\text{Mass}}\underbrace{C_v}_{\text{Specific Heat Capacity}}\overbrace{\Delta T}^{\text{Temperature Difference}}$$

REPRESENTATION

$$E = mC_v\Delta T$$



Thermal Energy $= \mathrm{m C_v \Delta T} = 3.75\mathrm{MJ}$


VARIATION
ΔT
50.0K
mass
50.0kg
Cv
1500.0J/kgK
Thermal Energy = mCvΔT = 3.75MJ
ΔT
50.0K
mass
50.0kg
Cv
1500.0J/kgK
Thermal Energy = mCvΔT = 3.75MJ
ΔT
50.0K
mass
50.0kg
Cv
1500.0J/kgK
Thermal Energy = mCvΔT = 3.75MJ

CONSTRUCTING THE REPRESENTATION

To start: construct a representation with:

Low mass
High temperature
High Heat Capacity

DRAW HERE

EXERCISE

Is there any energy difference, at room temperature, between:

50kg of copper at 50C°

50kg of gold at 50C°

In your explanation, use the new representation to explore the two scenarios

$$E = mC_v\Delta T$$

50kg of copper at 50C

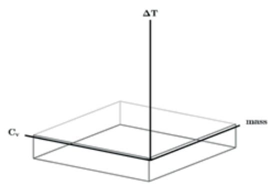
50kg of gold at 50C

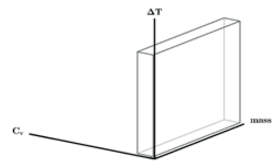
DRAW HERE $E = mC_v\Delta T$

Use the new representation to explore the two scenarios

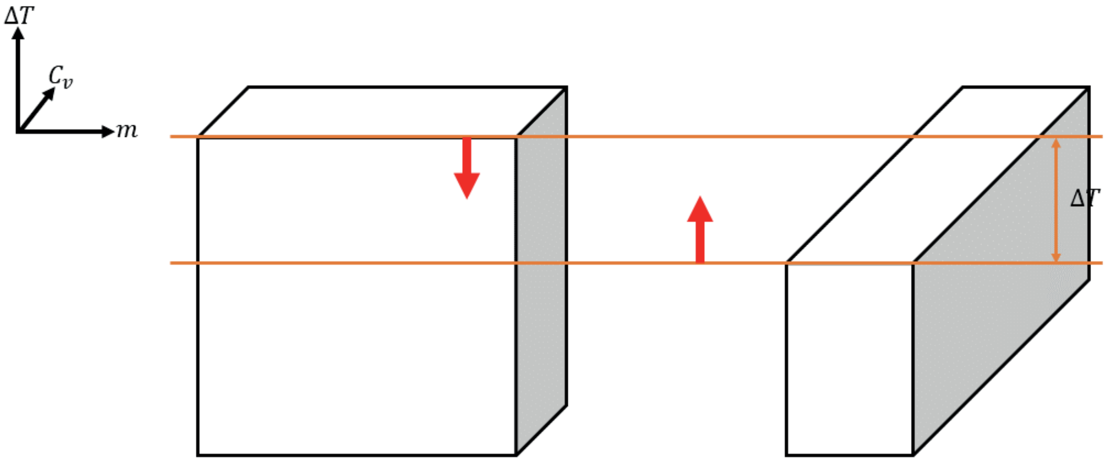
EXERCISE

Describe the two different objects shown here



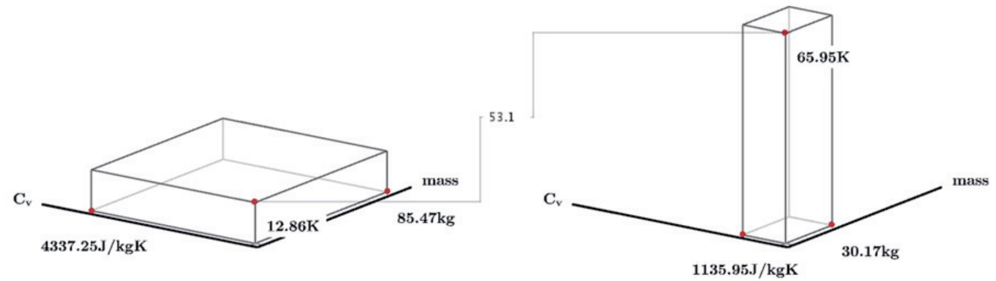


HEAT TRANSFER



What happens now?

HEAT TRANSFER



$$\text{Thermal Energy} = mC_v\Delta T = 7.03\text{MJ}$$

How would/could you use the representation?

DRAW HERE

About the author

KIM SVENSSON kommer från de småländska skogarna men började studera till civilingejör 2009 och har varit bosatt i Lund sedan dess. Under studietiden arbetade han som guide på science center och upptäckte glädjen med att lära ut och att undervisa. Han höll i ett antal programmerings-workshops för unga elever och programmerade aktivt på fritiden som i studierna. Direkt efter examen påpörjade han sin doktorand där fokuset blev att studera hur programmering kan användas som ett verktyg i fysikundervisningen. Forskningen kombinerar alla de vetenskapliga ämnen som Kim tycker är intressanta: Fysik, Programmering och Undervisning. Arbetet har sedan expanderat för att inkludera en mer teoretisk fokus där Kim utvecklar de ramverk som finns för att beskriva fysikundervisning.

KIM SVENSSON comes from the woods of southern Sweden but began to study for a Master of Science in engineering physics in 2009 and has been living in Lund ever since. During the study-period he worked as a guide at the local science centre and discovered the joy of teaching and learning. He supervised a number of programming-workshops for young adults and actively programmed in both his spare time and for his studies. Directly after graduation he began his work as a doctoral student where he began studying how programming could be used as a tool for physics education. The research combines the scientific fields that Kim finds interesting: Physics, Programming and Education. The work has expanded to a more theoretically focused approach where Kim aims to further develop the frameworks used to describe physics education.

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