"This pen is a rocket"

Semiotic Resources, Affordances and using programming in physics education.

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Semiotic resources, affordances and using programming in physics education

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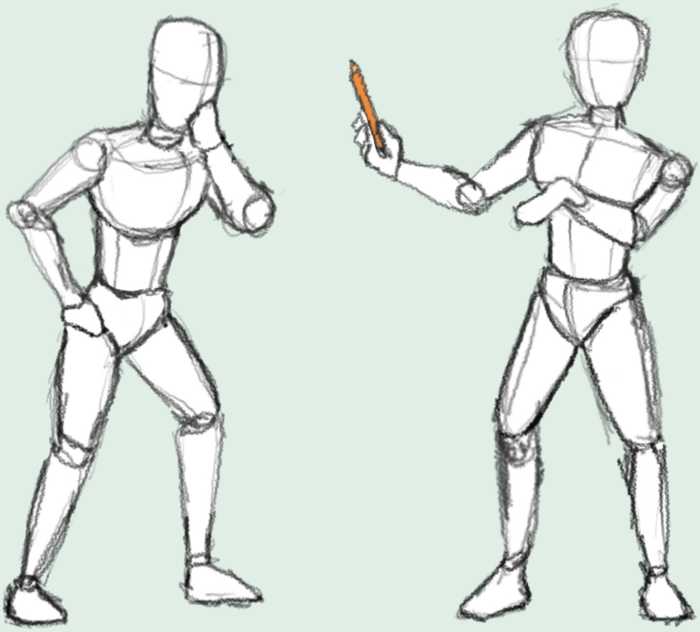

”This pen is a rocket”

Kim Svensson comes from the woods of southern Sweden but began to study for a Master of Engineering in technical 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.

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”This pen is a rocket”

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Semiotic resources, affordances and using programming in physics education.

by Kim Svensson

LUND UNIVERSITY

Thesis for the degree of Licentiate in Physics Education Research
Thesis advisors: Assoc. Prof. Urban Eriksson, Prof. Ann-Marie Pendrill
Faculty opponent: Assoc. Prof. Tobias Fredlund

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"This pen is a rocket": Semiotic resources, affordances and using programming in physics education.

Abstract

This thesis summarises approximately two years of my work in the physics education field. The main bulk of the thesis is about a pilot-study designed to study how programming may be used as tool for meaning-making in physics education and is covered in papers I and II. The thesis starts with a short history of the physics education research field and how programming has been explored in physics education in the past and what is currently being researched. A comprehensive description of the different theoretical frameworks used in this research; Social Semiotics, Variation Theory of Learning, Multimodality, Anatomy of Disciplinary Discernment and the concept of Affordances, follows after the literature review. The pilot-study inspired further development of the theoretical frameworks, especially focusing on semiotic resources and their interactions and modification combined with multimodality. The first result can be seen in the draft paper IV. Papers I and II explain and explore how programming can be used as a tool for meaning-making in physics education and identifies some important aspects that are inherent to programming: the ability to get instant feedback and to enter into a feedback loop, the explicit transduction of formulas into code and animations. Using programming, students can construct their own semiotic resources and programming may act as a transductive link between different semiotic systems. This is explored in paper IV. Paper III was a small departure from my main work and studies first year university students understanding about circular motion. However, paper III was analysed using social semiotics and variation theory and discovered that depending on how the problem is presented to the students will impact how the students will attempt to solve the problem.

Key words

Physics Education Research, Theoretical Framework Development, Social Semiotics, Variation Theory, Affordance, Multimodality, Programming, Meaning-Making

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MADE IN SWEDEN

I have no special talents. I am only passionately curious.
Albert Einstein 11 March 1952

Contents

List of publications

This thesis is based on the following publications, referred to by their Roman numerals:

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

K. Svensson, U. Eriksson, A-M. Pendrill and L. Ouattara
Journal of Physics: Conference Series (JPCS), International Conference on Physics Education 2018. in press

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

K. Svensson, U. Eriksson and A-M. Pendrill
Physical Review Physics Education Research, under review with revisions

III **Students making sense of motion in a vertical roller coaster loop**

A-M. Pendrill, M. Eriksson, U. Eriksson, K. Svensson and L. Ouattara
Phys. Educ. 54 (2019) 065017 (13pp)

IV **The concept of a Transductive Link**

K. Svensson and U. Eriksson
Draft manuscript

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Popular summary in English

I have examined how programming may function as a tool for learning physics using the theoretical frameworks of Social Semiotics and Variation Theory of Learning. Programming offers a possibility to implement physical models and ideas into code and animate and visualise the results. This path, to start with a formula and end with an interactive simulation, is called a Transduction and describes the operation of moving from one semiotic system, 'formula', to another, 'interactive simulation'. A pilot-study was conducted during May of 2018 with the purpose of studying upper secondary school students' experience with using programming in a physics education setting. The result of the study can be read in the papers I and II. The conclusion from the papers suggest that programming may be used for meaning-making in physics in a way that is qualitatively different from standard physics education.

Programming offers the possibility for students to take control over their learning processes and in particular the transduction process and decide how a formula is implemented, how it is calculated and how it is represented graphically. This adds explicit requirements on the student to unpack the formula into its parts and to understand how these parts work to create a functioning simulation. It is because of programming's unique implementation-process that the student can gain a deeper understanding of different physics concepts.

With the help of programming, the student can create their own semiotic resources where they may vary different aspects. The semiotic resources can be simple graphs, but also complicated interactive simulations or animations that are created with the purpose of conveying a specific disciplinary meaning. By letting the student decide how and what is shown in the new semiotic resource, they may balance the different affordances of the new semiotic resource to better facilitate their own learning process.

Affordances are a semiotic resource's meaning-potential, that meaning which it is possible to discern from a semiotic resource. Sometimes expert knowledge is required in a specific discipline to discern specific knowledge from the semiotic resource.

The paper *The concept of a Transductive Link* is a description of the transductive link concept and how links can be combined to create a transductive chain. A transductive link is what is used to transduce between two different semiotic systems. Programming is used as a transductive link between the semiotic systems 'formula' and 'interactive simulation' in the papers I and II. Which and how a transductive link is used plays a major role in the how the final semiotic resource will turn out and how well it can be used in the meaning-making process.

Populärvetenskaplig sammanfattning på svenska

Jag har undersökt programmering som ett verktyg för lärande i fysik med hjälp av de teoretiska ramverken Social Semiotik och Variationsteori. Programmering erbjuder en möjlighet att implementera fysikaliska modeller och idéer i kod och animera och visualisera resultatet. Denna väg, att gå från en formel till en interaktiv simulering, kallar vi för en Transduktion som beskriver operationen att gå från ett semiotiskt system, 'formel', till ett annat, 'interaktiv simulering'. Under maj 2018 genomfördes en workshop med syfte att studera gymnasieelevers upplevelse av att använda programmering i ett fysikinlärningssammanhang. Resultat av denna studie kan läsas om i papprena; *Programming as a semiotic system to support physics students' construction of meaning: A pilot study* och *Programming and its Affordances for Physics Education – A Social Semiotic and Variation Theory Approach to Learning Physics*. Sammanfattningsvis säger papprena I och II att programmering kan användas som ett verktyg för lärande i fysik som skiljer sig kvalitativt från en klassisk fysikundervisning. Detta förklaras utifrån lärande teorierna: Social Semiotik och Variationsteori.

Programmering erbjuder en möjlighet för studenter att ta kontroll över transduktionsprocessen och själva bestämma hur formeln implementeras, hur den beräknas och hur den ritas upp. Detta medför krav på att formeln måste packas upp och dess delar måste förstås för att en fungerande simulering ska skapas. Det är tack vare programmeringens implementeringsprocess som studenten kan få en djupare förståelse av de fysikaliska koncepten.

Med hjälp av programmering kan studenten skapa egna semiotiska resurser där hen kan variera olika aspekter. De semiotiska resurserna kan vara simpla grafer, men också interaktiva simuleringar eller animationer som är skapade för att förmedla en viss typ av disciplinär kunskap. Genom att låta studenten själva bestämma vad och hur som visas i den nya semiotiska resursen kan studenten balansera den semiotiska resursens affordanser.

Affordanser är en semiotisk resurs meningspotential, d.v.s: vilken mening som är möjlig att urskilja från den semiotiska resursen. Ibland krävs expertkunskap inom en viss disciplin för att urskilja specifik mening.

Pappret *The concept of a Transductive Link* är en kortare beskrivning av fenomenet av en transduktiv länk och hur denna kan kopplas ihop för att skapa en transduktiv kedja. En transduktiv länk är det som används för att gå mellan två olika semiotiska system. I papprena I och II används programmering som en transduktiv länk mellan 'formel' och 'interaktiv simulering'. Vilken transduktiv länk som används och hur den transduktiva länken används spelar stor roll på den slutliga semiotiska resursen och därför också på hur den kan används för meningsskapande.

Introduction

1 Introduction

This thesis is a summary of approximately two years of my research in the physics education research field. It focuses on my own proposed area of study: Using programming as a tool for meaning-making in physics education. The topic emerged from my own experience and interest into programming and physics simulations. I had used programming to understand different physical concepts or problems, such as the double pendulum system, or rudimentary fluid dynamics, during my time as a student. The hope was that my experience with using programming as a tool for meaning-making was not an isolated event, but that it could be reproduced with different students. The journey has taken me through a literature review of the physics education field, creating a qualitative data collection study using different theoretical frameworks, studying the data management rules of the General Data Protection Regulation (GDPR), becoming fascinated with discernment and affordances, analysing data using qualitative methods and presenting the results. The first pilot-study of using programming with interested upper secondary education students (paper I) is accepted for publication and a theoretical analysis of programming as a tool in physics education is under review (with major revisions 2020-02-16). The work has spurred an interest in understanding representations and semiotic resources, with the resulting paper IV and future work focused on the structure of semiotic resources and their dynamics.

1.1 The use of language

The purpose of this thesis is to collect and present the research and knowledge gathered by me during the first two years of my PhD education. It aims to capture my first-hand experience and my journey into the field of Physics Education Research. As a result of this I have decided to write this thesis from a first-person perspective but the research papers are all in third-person. The purpose of the thesis is to showcase my research and my experience with the new concepts and my personal take on them. The research papers are the culmination of this research and the experience that I have gathered during these two years. Within the thesis, I have chosen to adopt the gender-neutral pronoun of 'they' instead of 'he/she' to create a better flow in the sentences, but also to acknowledge persons that do not identify as either 'he' or 'she'.

1.2 Who should read this licentiate thesis?

If you have an interest in what and how programming could be used as a tool in disciplines separate from the programming-classroom, namely physics, this thesis is for you. The thesis aims to provide an example of programming as an educational tool for the student to use, using the lens of social semiotics and variation theory of learning. The thesis also delves into the theory of social semiotics and variation theory and in future research I aim to investigate the structure and dynamics of semiotic resources themselves. Papers I, II and III are focused on observations and interviews with students about different learning experiences and can be used to inform your own teaching of physics concepts. The programming focuses on using a particle-based physics engine, coded together with the students, to create and explore different physical concepts, both in the implementation of the code but also in the visualisation and the interaction with the simulation. Paper IV is theoretically focused and explores how semiotic resources (see section 3.1) can be modified and used to ease or hinder the process of moving between different semiotic systems.

1.2.1 Aims and purpose

The aims of the research performed here are three-fold: first, to get a better understanding of how programming can be used in physics education, using the theoretical frameworks of social semiotics and variation theory as analytic tools. The aim is practical; studying how programming can be used to enhance the learning experience by students. Second, analysing programming theoretically to provide a framework for the observed usage of programming. The results of this can be read in papers I and II. Third, and based on the results emerging during the analysis and writing of papers I and II, and in relation to the two previous aims, to expand the theoretical understandings of semiotic resources and affordances using a mathematical description. The beginning of the ideas for this can be seen in paper IV, however, the bulk of the work is yet to in a state to be published or presented.

1.3 Research questions

Based on the aims above, the research presented in this thesis can be summarised as exploring the following research questions (RQs):

1. How may programming be used as a tool for enhanced meaning-making in physics education using the ideas from social semiotics and variation theory?
2. How can affordances be used to compare semiotic resources with each other?
3. How does a modification of a semiotic resource change its affordances?

RQ1 represents the start of the research and my initial approach to doing research in the field of PER. By focusing on a single potential learning tool–*programming*–the analysis can be detailed and focused, showcasing its usefulness and drawbacks. Programming has been investigated before in physics education and PER (see section 2), and the unique approach in this research is the usage of the theoretical framework of social semiotics (3.1) and variation theory (3.2), that are relatively new theoretical frameworks that have previously been explored in PER by, for example, Airey and Linder (2017); Fredlund (2015) and Fredlund et al. (2014). RQ2 were natural extensions of RQ1 as I analysed the data for papers I and II. A need to compare different semiotic resources emerged from studying students' creation of different semiotic resources using programming and modifying the semiotic resources. Paper IV is my attempt at answering parts of RQ2 and RQ3 with further research being done as part of my doctorate.

1.4 The knowledge claims of this thesis

The work of this thesis started by looking at programming as a tool for meaning-making but have evolved into a theoretical analysis of programming and what it affords for the learning process, combining the theoretical frameworks of social semiotics and variation theory. The practical programming were done with interested upper secondary school students and with interested upper secondary physics teachers with the aim to investigate the affordances of programming for physics education.

This thesis thus provides a detailed analysis of programming using social semiotics (section 3.1), variation theory of learning (section 3.2), Kolb's learning cycle (section 3.4) and the anatomy of disciplinary discernment (section 3.5) to expand the knowledge about the learning potential of using programming in physics education. The analysis of programming has required further work into understanding the structure and dynamics of semiotic resources and paper IV is the start of this research. Further research into modelling semiotic resources using affordances and the dynamics of semiotic resources are underway.

1.5 Structure of the thesis

The thesis begins with this introduction (chapter 1) followed by a literature review and an overview of the physics education research field (chapter 2). It then evolves into an exploration of what role programming has had in physics education up to this point before delving into the different theoretical frameworks that has influenced my research (chapter 3). My research (chapter 4) comes next, which is separated into two parts; the first part pertains to the early work of creating a study and testing programming and the second part analyses programming and the theoretical frameworks used to analyse programming. Then comes the methodology (chapter 5) of the research with a focus on qualitative methods, the data collection process and the quality and reliability assurance of the work. After the methodology comes a description of the qualitative analysis for the different papers presented in this thesis (chapter 6). Each paper has a different focus and thus a different analytical approach. The results and conclusions of the research is separated into sections for each paper (chapters 7, 8 and 9).

Literature Review

2 Literature Review

Below follows a brief overview of the physics education research field with a short exploration into how programming has been used in physics education and the research surrounding it. It should not be seen as a total overview of the whole of the physics education research field nor of programming's role within the field, but it is a selection of important papers and ideas that have influenced my research and my future work within the field.

2.1 Conceptual Understanding and the History of Physics Education

Physics education research (PER) began in the era of Sputnik and the space-race between the US and the USSR, however I have chosen to start with the work of McDermott (1974) that investigated students conceptual understanding of different topics within the physics discipline and discovered that students had significant gaps in their understanding. Up until this point, most of the education in universities were done through normal lecture-based learning environments, a way of teaching that began in the 16th century when the word *lecture* emerged from the old word *lectus* meaning to 'pick out, select'. Lillian McDermott investigated how well standard lectures work as a learning environment and discovered that standard lectures barely increased the students understanding, see McDermott and Redish (1999) for a comprehensive overview of the findings. In the beginning of the 1980s the results from McDermott's research spread to the wider physics community and several others began their own studies into the emerging field of PER. David Hestenes of Arizona State University (Hestenes, 1987) wanted to quantify students conceptional understanding and developed the Force Concept Inventory Survey (FCI) together with Halloun, Wells, & Swackhamer. Redish (2014) reported that the FCI showed that students who performed well on standard calculation-based-tests performed badly on conceptional-based-tests, indicating that the standard lecture-format for teaching did not create understanding of the subject but instead only fostered raw calculating prowess. Many researchers in the PER field are using the FCI to measure how different teaching techniques or new learning strategies are performing, see for example Caballero et al. (2012a).

2.1.1 Moving away from Lecture-based education

Several new structures have been developed to move away from lecture-based teaching. Some of the most used are: Flipped classrooms by King (1993), Problem Based education by Wood (2003), Physics Workshop and Tutorials by Redish (2003), Modelling Instructions by Hestenes (1987), Think-Pair-Share by Lyman (1987) and more. Many institutions use a combination of all of the ideas when they adopt a non-lecture based learning environment, but many institutions are also sticking to traditional lecture-based education despite the researchers findings. Many researchers use the quantitative measurement of 'gain' to measure how well a new learning environment performs. To calculate the 'gain', a pre-test and a post-test must be performed, and the results are inserted in the following formula:

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

Eq.1 uses the percentages of the student scores to calculate the 'normalised gain': how much they improve between the pre and post-test. The FCI is commonly used as a pre- and post-test when studying the concept of force, see Caballero et al. (2012a). Each new classroom activity has produced higher scores on the FCI tests compared to the old lecture-based systems, indicating that they are better at ensuring the students learn and understand the concepts better in the new environment compared to the normal lecture-based setting. The conjecture is that by allowing the student to discuss and explore the topics themselves increases the understanding of said topic, some minor guidance is recommended when the students gets stuck or need to ask questions. To foster self-study and exploration of different subjects, the students' interest in the subject should be in focus and aimed to be increased.

However, the 'gain'-measurement does not tell us how the new learning technique works; only that it does. The new learning technique or learning environment are treated as a black box where the student acts as a probe. The student is sent into the black box and we measure the student after it comes out, unable to see what it was in the black box that produced the change in the student. Social semiotics (3.1) attempts to describe this increase in understanding by studying how students use different semiotic resources and semiotic systems to understand different concepts with a focus on understanding what guided a change in the students conceptual understanding. By looking at the variation and the transduction of semiotic resources used in the new learning technique or environment, an understanding of the hidden process in the black box can be gained.

2.2 Physics Education Research (PER)

Physics Education Research (PER) is not a field with strict rules and conjectures, as opposed to the actual field of physics with its laws of conservation and interactions between fields. This gives PER a very open playing field and researchers are constantly exploring and finding new angles to interpret or adapt physics education all the time, often building on methods and theories from social sciences. The research up to this point has very much been focused on creating new classroom experiences and documenting their improvement through different surveys. Different gain-measurements have been devised to measure the change in student understanding about different physics concepts using new classroom experiences and these new classroom experiences have been optimised to improve these gains. Lately, the field has turned into an analytical research field where explanations of *why* these novel classroom methods work have come into focus. The field has produced reproducible gains across multiple schools and ages and are trying to explain these findings. This should not be interpreted as a total shift in focus; many researches are still trying to come up with better classroom experiences and new ways to increase the understanding of physics by students, however, a set of classroom experiences have been found to increase the understanding of physics concepts and theories from social science and education are used to understand them.

One of the first successful attempts to explain the understanding of physics is Andrea diSessa's model of phenomenological primitives (diSessa, 1993), which tells us that everyone has naive conceptions which we need to address in the classroom. diSessa breaks down conceptions into phenomenological primitives that are drawn upon when investigating or solving physics problems, these are called p-prims. P-prims are simple statements or ideas that are drawn upon, almost unconsciously, when students solve problems, such as: ”The Sun is smaller than the Earth” which is based on the personal observation that the Earth appears bigger than the Sun when we look out the window. Another p-prim is: ”More is more”, which means that stuff will just increase if we add more of it; the temperature of the boiling water will keep increasing if we leave it on the stove, or; the velocity will just keep increasing if we add more kinetic energy to the system. Using p-prims it is possible to break down the students understanding into chunks and tailor the teaching methods to address the different p-prims found within the student-body. One naive conception, or p-prim, that is often seen in physics students is the idea of the impetus force. The Impetus Theory (McCloskey and Kohl, 1983) states that forces acts over time and linger in the object they interact with. If a ball is thrown up, the force of the throw still acts after the ball has left the hand, but its strength is decaying with time. The impetus theory goes hand in hand with the p-prim ”force equals motion” that encapsulates the idea that a force is required for motion to take place. A comprehensive list of many naive conceptions has recently been published by the Institute of Science (Institute of Physics and Hardman, 2019). The list is composed of a large number of research papers in PER from the 1970 to today.

2.3 Programming in PER

Programming has already been used in physics education and have been studied by the physics education research community, see for example, Papert (1980); Wilson and Redish (1986); Redish and Wilson (1993); diSessa (2001); Abelson and DiSessa (1986); Bocconi et al. (2018); Alexandron et al. (2017). Using the MUPPET program Redish and Wilson (1993) investigated the role of computers in physics education and how compared it to the role of computers in physics research. They found that researchers often used computers to test models and to get approximate solutions to inexact models whereas students used analytical models to get exact solutions to inexact models. The physics researchers did not see the laws as fundamental, but ideas to test and discover, however the students saw them as unchanging concepts that could not be the subject of hypotheses. Redish and Wilson (1993) hoped that the introduction of using computers would allow for more interesting problems for the student to solve and to make the physics education setting resemble the physics research workflow. The aim was to provide the student with another tool for investigating physics, not to replace the current resources used in the classrooms. They found that two thirds of the physics master students were able to construct interesting physics projects using their MUPPET program. Papert (1980) takes the same view as Redish and Wilson (1993) where it is not the program that should teach physics to the students, but it is the student that should program the computer to learn physics, Papert takes a broader view of the education and looks at programming and logic whereas Redish looks only at physics. One of the projects the students came up with in Redish and Wilson (1993) was to model the forces of a Frisbee, which is also one of the spontaneous projects that emerged during the pilot study of my project (see papers I and II), which acts as a validation of the work of Redish. However, my students were upper secondary education students and not master students, but programming triggered the same idea in both cases, see papers I and II.

My research differs as it attempts to analyse programming itself, from a physics education research perspective, using the theoretical frameworks of social semiotics and variation theory.However, the ideas from Redish and Wilson (1993) and Papert (1980) are still present in my research; that the student should be the one using programming to explore and create physics, programming should not be used to demonstrate or to plug'n'chug different physics concepts. Programming should be seen as tool for the students to use when they explore and investigate physics, similar to how mathematics (graphs, plots, images) are used to investigate different physical phenomena in physics education. The main research points, gained from the early research in the eighties, was that programming had the potential to be used for understanding physics, but also that it was difficult, both for the student and for the teachers since they were not used to programming. With faster computers and higher level programming language, programming has once again come up as a research interest in PER. Some recent research into using programming, or fostering computational thinking can be found in: Caballero et al. (2012b); Gerestrand (2017); Dwyer et al. (2014); Sand et al. (2018); Chabay and Sherwood (2008, 2004). The research aims to look outside of programming itself and studies what mental models or what mindset programming instils or foster in the student, such as computational thinking or algorithmic thinking, and attempts to induce them outside of a programming setting. Programming have been used to construct different animations or simulations for use in physics research. The effects of animations and simulation on conceptual change have been studied by e.g., Chang et al. (2008); Trundle and Bell (2010); Bell and Trundle (2008), in a variety of disciplines, and they found that animations and simulations can be used as tools to foster conceptual change if they are used in the correct way. Chang et al. (2008) found that allowing the students to make and test their own hypothesis allowed for greater conceptual change compared to just following step-by-step instructions. Trundle and Bell (2010); Bell and Trundle (2008) used the Starry-Night^{TM} planetarium program to study conceptual change in students understanding of the phases of the moon. They used a mix-method approach and found that just using the software to learn to draw the phases of the moon were as good or better than going out in nature to observe the phases of the moon. It is clear that simulations and animations can be used to learn different concepts from astronomy and physics.

The Swedish National Agency for Education (Skolverket, 2016, section 1.3) takes a broad view of programming and connects the act of coding with producing animations, computational thinking, algorithmic thinking and the ability to understand the role of programming in different settings with the term programming. Programming has also been introduced as an obligatory part of the mathematics education in Sweden to be used as tool to investigate mathematical phenomena or concepts. The American Association of Physics Teachers (AAPT) 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 a modern physics education (AAPT Undergraduate Curriculum Task Force, 2016).

However, the introduction of programming into physics education must be done with purpose and thoughtful consideration of all aspects. See Caballero and Pollock (2014); ?); Caballero (2015); Aiken et al. (2013) for considerations in how programming could be introduced into the curriculum. Lest not forget the work done by Chabay and Sherwood (1999, 2004) with the Matter and Interaction textbooks which restructures the whole physics curriculum to be based on computational physics.

2.4 Summary of literature review

Work has been done on how to use programming in physics education, both recently and in the past. The research results are mixed due to the different approaches to introducing programming and the time it was introduced. In the seventies and eighties, not many students had experience with programming, or even computers, and the computers today are much faster with higher level programming languages which provides the potential for doing more advanced simulations using a easier-to-read programming language. However, the ideas that emerged around using programming in physics education as a tool to be used by the student to investigate and explore physics are still valid today, especially now when many schools offer a laptop or tablet to each student.

Programming was identified as a tool with great potential for learning and meaning-making in physics education very early. More recent research are looking at everything surrounding programming and the techniques used when programming and how to apply them to physics education as a whole, such as computational thinking, debugging, creating algorithms and problem solving. No research has been done using the theoretical framework of social semiotics to analyse programming as a semiotic system to be used as a tool for meaning-making in physics education. This thesis will provide such analysis and argue for how and why programming is useful in a physics education setting.

Theoretical Framework

3 Theoretical Framework

During the two years leading up to this thesis, I have been introduced to many different theoretical frameworks, each with its own strengths and weaknesses. I will now describe the frameworks that I have chosen to use in my work and why these were chosen among all the available frameworks. The first broader framework is *Social Semiotics*, which studies group meaning-making through the use of semiotic resources. In papers I through IV, I study the use and modification of different representations by students and what this offers for their learning experience. Social semiotics offer ways to study students' use of semiotic resources and the production of new representations. Another theoretical framework, the *Variation Theory of Learning* (VTL), provides a way of quantifying what variations and modifications of semiotic resources offers the student in terms of how well they may discern or understand different relevant aspects. *Multimodality* offer a way of talking about different modes, such as text and images, in a unified manner and how to think about making modifications to them. Multimodality also provides the terms *Transformation* and *Transduction* which describes different types of modifications of representations. I also identify transduction as an important part of programming and its potential as a tool for learning. *Kolb's learning cycle* (KLC) offers a framework for describing the steps required to investigate or understand a certain concept. KLC was chosen since its structure corresponds well to the quick feedback loop provided by programming, but it also corresponds well with the scientific mindset and scientific method of investigation that we want the students to learn. The *Anatomy of Disciplinary Discernment* (ADD) offers a way of describing what a student discerns from a representation and their understanding of concepts that went in to creating that representation. This lens is used in conjunction with the idea of *Affordances*, or meaning potentials, that describes what a representations offers. It is the combination of all of these ideas that have shaped my research and my future work. In the following sections I detail the structures of the different theoretical frameworks and how they relate to my work on analysing programming and using programming as a tool for meaning-making in physics education.

3.1 Social Semiotics

Social Semiotics is the study of group meaning-making through the use of semiotic resources (Halliday, 2009; Airey and Linder, 2017) and has been used and expanded upon in the Swedish physics education research community for many years, see Fredlund (2015); Airey and Linder (2016); ?); Linder and Priemer (2013). With the start of the physics education research group at the National Resource Centre for Physics Education at Lund University, social semiotics expanded in the Swedish sphere from being centred in Uppsala University to having a research group at Lund University.

Specialised groups in society communicate using specialised language and by using different resources, for example: in the physics discipline we communicate using special words and mathematical formulas combined with graphs, images, animations and demonstrations or experiments. Each of the different ways of communicating meaning within physics, or any distinct discipline, are called semiotic systems. A semiotic system is a method of communicating meaning that is qualitatively different from other ways. 'Text' is qualitatively different from 'Image' in its usage and represent two different semiotic systems. Some standard semiotic systems in the physics education discipline are: 'Formulas', 'Graphs', 'Plots', 'Images', 'Animation', 'Text', 'Speech', 'Gestures', 'Demonstrations', 'Lectures', 'Exercises' and possibly many more, to convey meaning about different physical concepts or ideas.

Within each semiotic system exists a large number of different semiotic resources, each designed to convey a different meaning and to be used in a specific context or setting. Within the semiotic system 'Formulas' we have the formula $F = -kx$, Hooke's law, which models the force in a spring around the equilibrium in one dimension, the formula is a semiotic resource with a specific meaning within the discipline. However, by making a small modification to the formula: $F = -kx \rightarrow \bar{F} = -k\bar{x}$, we have created a new semiotic resource that may be used in a new way. Every formula in the semiotic system 'Formulas' is a separate semiotic resource, with a different meaning-potential for a student to discern. A single semiotic resource can be built up from other semiotic resources, from many different semiotic systems, such as a page in a physics textbook that uses both text, images and formulas to communicate the meaning of the physical concept under analysis. The page is a new semiotic resource that combines other semiotic resources to create a situation that draws from the strengths of the different semiotic resources to optimise the discernibility of a specific idea or concept.

Students must learn to read and manipulate the different semiotic resources used within a discipline if they want to become part of that discipline. To learn to climb a mountain you must first learn the techniques, how the gear works and the special language used within the field of mountain climbing, these are the semiotic resources of mountain climbing. However, students within the discipline may also construct their own semiotic resources that they use to explore and understand different concepts or ideas. This is a departure from the

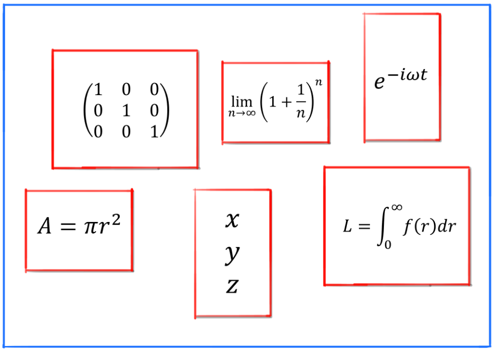


Figure 1: Different semiotic resources within the semiotic system of formulas. Each of the semiotic resources uses the same symbolic base, but are used to convey different meaning. The meaning that is discerned from them depends on the student and the context they are in. However, within the physics discipline, they have some agreed upon meaning.

strand of social semiotics from the Uppsala PER group which studies already established semiotic resources within physics and physics education. I draw upon the framework created by Russell Tytler (Tytler and Prain, 2010; Prain and Tytler, 2013) to argue that student created semiotic resources are still valid semiotic resources even if the new resource has not been established within the discipline. Russel Tytler argues student created representations should be used to spark conversations and discussions about concepts and ideas to create an environment for learning in physics education. I argue that Tytlers ideas and social semiotics are very closely linked and I will use the ideas from both frameworks in my analysis of programming in papers I and II as I study student created semiotic resources.

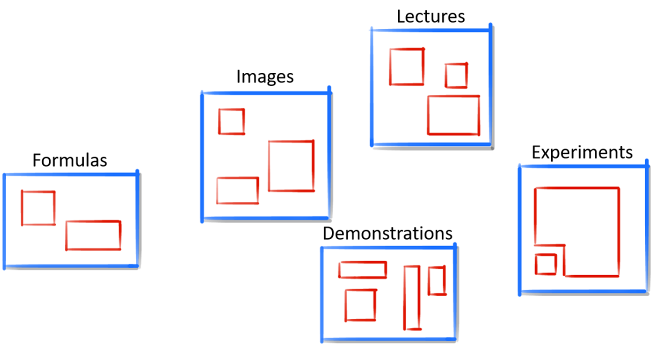


Figure 2: Different semiotic systems all with their own semiotic resources. The different semiotic systems are qualitatively different from the other systems.

Programming can be described as its own semiotic system since it has its own unique way of representing concepts and programming has its own way of manipulating the representations. The way the code is written depends on the specific syntax of the programming language at hand, however, they all employ some version of algorithmic or computational thinking, to create the implementation of a concept. Using programming as a semiotic system, new semiotic resources can be constructed and manipulated. These semiotic resources could be representations that are similar to the ones used by physicists in their daily work such as plots or graphs, but they could also be new semiotic resources with the sole purpose of showcasing a specific aspect that are not of interest in the broader physics discipline, but is interesting in this specific setting and scenario in this specific group of students. Such as showing how the orbit of a planet does not depend on the colour of the planet itself using different simulations with different coloured planets. The new semiotic resource, the animation, would be created to showcase this specific scenario and designed with this meaning in mind. However, it would be hard to find a similar semiotic resource in any physics education setting. In this thesis, I focus on the creation and usage of physics simulations and not on the general ideas or theories used in programming as a whole, such as algorithmic thinking, the semiotics of programming language or the syntax of programming languages.

3.2 Variation Theory of Learning

The term variation theory can be confusing if the person reading this comes from the mathematical or physical sciences where variation theory is a method in mathematics to analyse and optimise systems or problems. In these settings, variation theory refers to the technique of introducing a small variation in a variable and optimising the solution using this variation, such as minimising the total energy level in a system by varying the width of the potential well.

However, this is not the same as the variation theory of learning (VTL) presented below, but both theories use variation of aspects as a central part of their function. Variation theory of learning aims to understand and identify what is necessary to learn and have been investigated by Marton and Booth (1997). They observed that the unifying factor of learning different concepts was the variation one experienced within that concept. By varying a single aspect, while keeping the background the same, that specific aspect could be discerned and identified as its own object, separate from the background. For example, by only varying the velocity in the x-axis in a two-dimensional simulation of a ball, the x-velocity can be discerned to be separate from the y-axis and the y-velocity. Marton (2015) argues that to even have the possibility to learning of an aspect, one must first be made aware of said aspect. This is done by discerning the aspect. If that aspect can be identified as its own thing, separate from the background, it has been discerned and may be studied to further the understanding of the aspect. For example; when Hewish et al. (2014) discovered pulsars, it was because the signal stood out from the background. Pulsars, a dense small stellar core left over after a supernova explosion with a strong magnetic field, sends out beams of electromagnetic radiation from its magnetic poles. As the pulsar precesses, and points towards Earth, we may detect these pulses at regular intervals. These regular pulses stood out from background and could be identified as a new aspect of the cosmos. The ability to distinguish the signal from the background, due to its variation, was what allowed the researchers to discern and identify the signal as a new aspect.

Variation theory states that discernment is a necessary requirement for learning and that discernment requires variation. By varying only a single aspect, that aspect is highlighted and possible to discern. If the background is varied, instead of the aspect, too many aspects are varied and it is much harder to discern the single aspect that is static among everything else. Variation theory can be used as a guide when developing learning environments, see for example: Kullberg et al. (2017); Lo (2012b), and have been used as an analytical tool for studying learning environments, see for example: Thuné and Eckerdal (2009).

In fig.3, we wish the student to discern the phenomenon of 'colour'. To facilitate this discernment, we introduce a variation in the 'colour'-aspect from green to blue. The student can connect the change that they are seeing with the aspect of 'colour' and the different dimensions of the 'colour'-aspect. However, if we vary more than one aspect, see fig.3 upper row, the student sees two aspects that change, its colour and its shape, and it is harder to discern which one of corresponds to the 'colour'-aspect that we are interested in. By only varying the *relevant aspect*, we ensure that that aspect is in the focal awareness of the student and discernible. Any aspect that is not in the focal awareness is considered part of the background, even if they are part of the object that is modified, such as the shape in fig.3 in the second row.

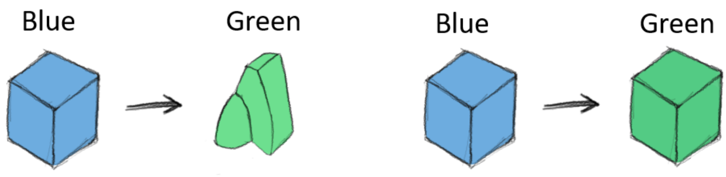


Figure 3: The colour of the cube is varied, from blue to green, in two different scenarios. On the left side, both the colour and the shape changes and right side, only the colour changes. It can not be discerned from the left side, if the term 'Green' refers to the shape or the colour of the object. However, on the right side, it becomes clear that it is the colour of the object that should be identified with 'Blue' or 'Green'. By keeping the background the same and only varying the important aspect, that aspect can be discerned.

3.2.1 Dimensions of variation

When variation is created, it is said that a *dimension of variation* is opened up for that aspect. The dimension of variation can then be explored and understood. A single item may have several dimensions of variation that can be explored, such as a ball's mass, radius, colour, bouncyness or other aspects. A dimension of variation is opened when an aspect is varied, however, it is not necessary to just open up the dimension, it must also be explored for discernment to take place. For example: By saying the phrase: "The ball may could be light or heavy", we open up the dimension 'mass' to be varied and explored. However, we have not explored the new dimension and we can not except our students to discern the meaning of the mass of the ball. Sure, the student may understand that the mass can change, but they do not know what that means for the system; they have not discerned its meaning in a disciplinary context. That is, they have not been provided the opportunity to understand what role mass has in physics, or in this physics-related situation; students and teachers may open up different dimensions of variation (Kullberg, 2012), but may fail to explore them. In fig. 4, the dimension 'blue' is opened up and explored by showing different variations of the colour 'blue' against a static background. The shape does not change and the white background does not vary. It is through the exploration of the dimension of variation that an understanding of the aspect can be obtained. The exploration may also help identify how the aspect fits into the larger system. For example: a single variable in the code may be changed to study how that specific variable affects the system.

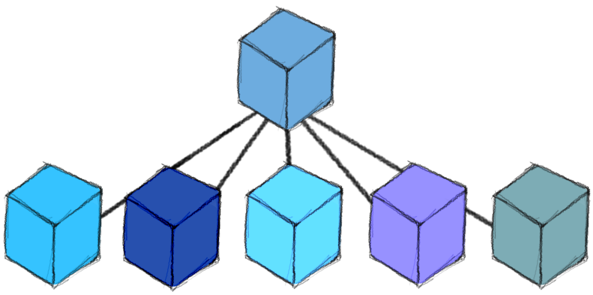


Figure 4: The dimension 'blue' is explored by varying the amount of 'blue-ness' the cube has. This can be further subdivided into value, hue and saturation. It is through the exploration of the aspect that a deeper understanding of it can be gained.

3.2.2 Relevance Structure

Marton and Booth (1997) identified an awareness structure in variation theory of learning that they call 'The relevance Structure'. The relevance structure describes what a student finds relevant in a particular situation or problem. When a student throws a ball to hit a hoop, they may not think the Moons gravity is relevant to the balls motion and disregard its effects in their calculation. This is an example of where the relevance structure is correct, the Moons gravity will not affect the balls trajectory in a measurable way. However, if they do not think the angle of the trajectory is relevant, they will probably miss the hoop. In fig.5, two different relevance structures are shown, one that takes into account the angle of the trajectory, one that does not. The angle of the ball's trajectory is relevant, but it may be outside a students relevance structure and they do not consider it important, with the consequence being that they miss the hoop.

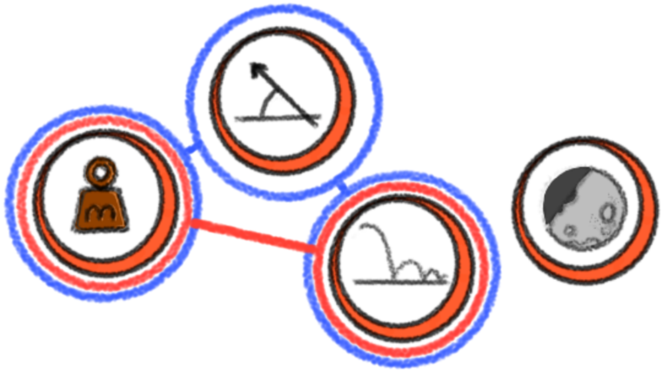


Figure 5: The figure shows an example of a relevance structure for a person throwing a ball. The red outline encapsulates what the disciplines (physics) finds relevant and the blue outline encapsulates what a person may find relevant. Note that this only shows a subset of aspects: mass, bounce, angle and the moon. Many more aspects play a role, and even more aspects are irrelevant.

Through the use of variation of different aspects, a learner can discern and discover what is relevant for different situations. From this knowledge, more general rules can be formulated and understood. Variation helps shape the relevance structure of a learner through discernment and discovery of the effects of different aspects. The relevance structure is dependant on the lens used to study the said phenomena (throwing a ball); the phenomena can be seen from a physics discipline, with its forces, vectors and differential equations, or it may be seen from an artistic perspective by a director when filming a movie. A director's relevant aspects are probably related to the framing, lighting, timing and acting of the ball-throwing scene and not to the physics behind the ball-throw itself. In this thesis, the relevance structure is seen through the lens of the physics discipline, or the physics education research discipline, unless specified differently. In paper III we see an example of how the students relevance structure affect how they solve a problem. The aspect a certain discipline finds relevant are called Disciplinary Relevant Aspects (DRA), see Fredlund (2015). For a certain concept certain DRAs must be discerned by the student before a complete understanding of the concept can be obtained. The use of variation theory should be to highlight the specific DRAs for the concept currently being taught.

3.3 Multimodality

The theoretical framework of Multimodality (?Kress and van Leeuwen, 2006; Jewitt et al., 2001; Kress et al., 2014), aims to describe how the use of different *modes* together affects the learning process. The idea originated from the idea that we process different sensory information differently, or even at the same time. A mode is characterised as different ways of representing a situation, idea or concept. However, a precise definition of what modes are is under debate (Mavers and Will, 2020), but text, images, formulas, speech are all examples of different modes, but the medium of presentation is also important and a pamphlet is a different mode compared to a book since they present information with different intended settings. Multimodality, as the name suggests, studies learning process when multiple modes are used together, such as using text and images together on a page. It studies the layout, the content, who the audience is and how to move between the modes.

In this thesis, I have chosen to explore what moving between modes provides in a programming and a physics education context. Bezemer and Kress (2008) describes two different ways of modifying modes: *Transformation* and *Transduction*. A modification of a mode refers to changing the content and/or the medium of the representation.

3.3.1 Transformation

Transformation refers to a modification of a representation that preserves its mode. Rewriting a text to conform to another audience is a transformation. The intended meaning of the text is approximately the same, but it is phrased in a new way to conform to the audiences' knowledge or interests. Transformations can be very powerful tools to apply when using different representations in a learning environment. By modifying the representation, it could become more readable, or specific aspects can be highlighted. One of the simplest transformations could be to just change the background of a powerpoint presentation to another image or colour to make the text more readable. In fig.6, the text has been modified from "Hello" to "Hi!!", this modification retains the same information, a greeting, but the perceived tone and intent are different.

3.3.2 Transduction

The second way to modify a representation is to change its mode. When a modification takes one representation from one mode to another, it is called a transduction. For example, a transduction is performed when moving from a formula to a plot, the same information is represented two different ways. In fig.7 we see an example of a simple transduction where a text is transduced into an image of a ball.

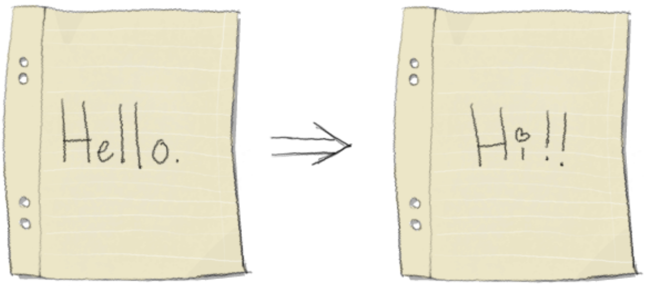


Figure 6: The figure showcases transformation. The text is modified to convey a different tone or intent but retains its information and stays within the same mode or semiotic system.

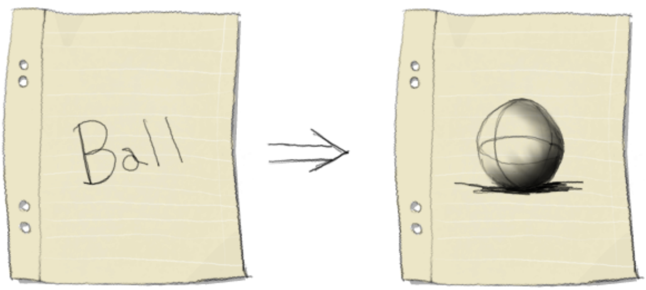


Figure 7: The figure showcases transduction, text is transformed into an image. A semiotic resource is transduced into another semiotic resource. This takes the object from one semiotic system or mode: Text, to another semiotic system: Image.

Transduction requires the transducer to answer many different implicit questions in the process. In fig.7 some of the implicit questions are: "How large is the ball?"; "What colour is the ball?"; "Is it a realistic or stylistic image?"; "Does the ball have a shadow?"; "Where is the ball?"; "Does the ball move?"; and many others. Each question is required to create the image of the ball itself. The text-mode of 'Ball' does not require the user to answer any of these questions as the text-mode representation is constructed.

3.4 Kolb's Learning Cycle

Programming introduces an iterative approach to physics modelling and understanding through its ability to quickly test and verify different solutions or implementations. This approach is well matched by Kolb's learning cycle, named after Kolb (1984), that aims to describe the learning process. The process is divided into four different phases as seen below. The student moves through the different phases and will end up going through several cycles in the learning cycle as their understanding of different concepts deepen. The cycle also reflects the scientific method that physicists, and other scientists, use in their work as they explore and discover new methods or phenomena.

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

The cycle moves from concrete experience to reflection to abstraction to hypothesis and finally back to concrete experience. As a student learn, 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 since the implementation of simulations often takes on this cyclic, or iterative, approach (see Allen and Tildesley, 2017). The act of studying the simulation provides opportunity for reflection: ”Does it do as I want?”, which in turn leads to abstraction. For example: ”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 potentially could take months or years to learn, or very small aspects such as learning the meaning of a for-loop. It is also desirable to perform several turns through the cycle, each turn provides new insight into the idea or concept that is being studied. Kolb's learning cycle also provides a checklist of learning opportunities that should be provided to the students in order to facilitate learning (Elmgren and Henriksson, 2015). 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.

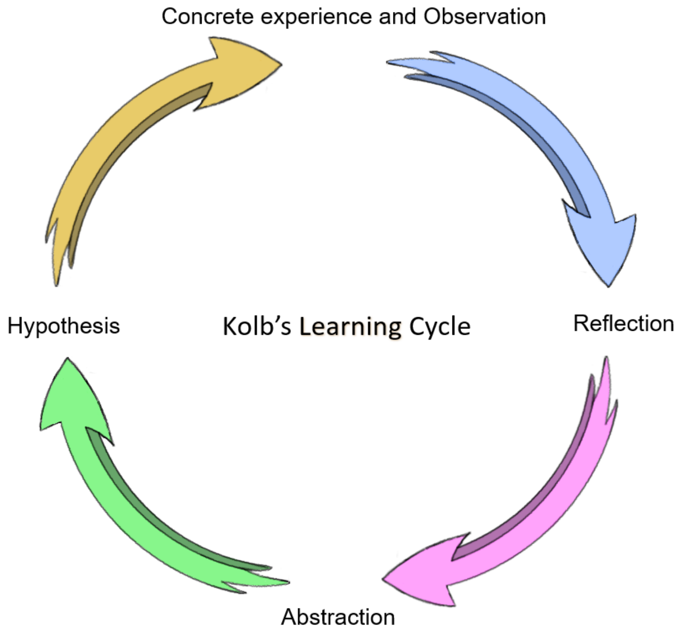


Figure 8: The figure showcases Kolb's learning cycle. A learner moves between each stage of the cycle and gains a deeper understanding of a subject or concept. The different stages are designed to flow from one to another: After an observation it is natural to reflect on it. The reflection may give rise to some insight that is used to abstract the observed phenomena or situate it in a theoretical framework. From the abstraction, new questions may arise that develops in to new hypothesis that can be tested.

3.5 Disciplinary Discernment

Within this thesis the term 'discernment' is used a lot. It should be noted that discernment in these cases refers to 'disciplinary discernment' by Eriksson et al. (2014), where the discernment is related to the discipline at hand, such as the physics discipline. Urban Eriksson, co-author on the articles presented in this thesis, supervisor and the mind behind the Anatomy of Disciplinary Discernment (ADD), has studied what students and professionals discern from different representations, in the astronomy discipline, and have developed a hierarchy of disciplinary discernment, see fig.9.

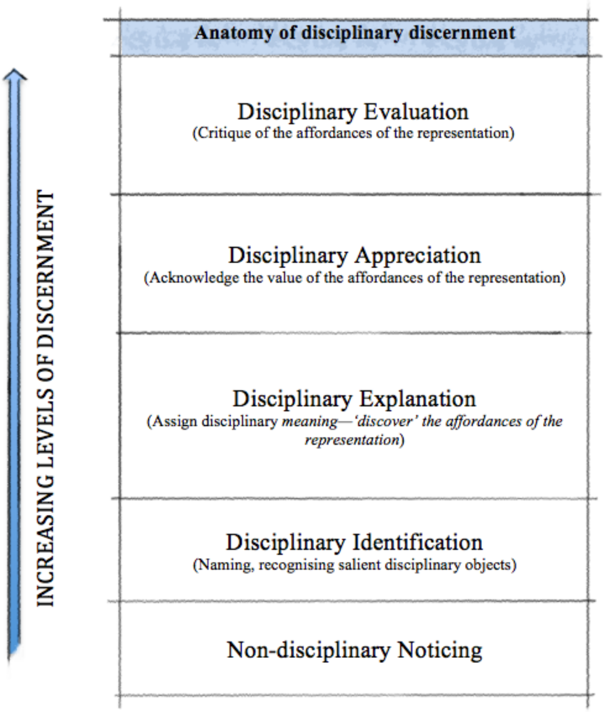


Figure 9: The figure showcases the Anatomy of Disciplinary Discernment. As their knowledge and understanding increases, the student will discern more disciplinary relevant aspects. Source: Dr. Urban Eriksson (Eriksson et al., 2014), reprinted and re-stylised with permission.

Using the space image in fig.10 we can investigate the different levels of the ADD hierarchy. The five categories in the ADD are (paraphrased from Eriksson et al. (2014)):

Non-disciplinary Noticing The student discerns different representations within the resource, however, they are unable to identify what they are or explain them in a manner were disciplinary knowledge can be inferred. The student can see that the dots have different colours and shapes, but are unable to say if they are stars, galaxies or something else related to space, if they were to look at an image from ESA or NASA.

Disciplinary Identification The student is able to identify disciplinary relevant aspects but has no explanation for them. They can identify that the small dots are stars and the large blob is a galaxy, they might even provide them with names, such as Betelgeuse or Sirius. However, they are unable to provide an explanation for why the stars are red/yellow/blue, or why some appears brighter or dimmer than others.

Disciplinary Explanation The student are able to give disciplinary relevant explanations for why certain disciplinary relevant aspects are represented in certain ways. They can provide an explanation for why the stars differ in their colour and intensity.

Disciplinary Appreciation The student acknowledges the disciplinary affordances (Fredlund et al., 2014) of the resource. For example, the student may comment on the clarity of the colours of the stars, which highlights the discernment of the stars dynamics and composition, or they may acknowledge why just this piece of space was chosen to be represented in the resource since it may be an area with a diverse selection of different coloured stars.

Disciplinary Evaluation The student can critique the resource for its misrepresentation or for how the resource is used. This requires a high degree of disciplinary knowledge but also a high degree of pedagogical understanding of the resource and how it may be used. The student may identify that the representation is a combination of several false-colour images of some astronomical phenomena and points out that this might be misleading or provide a distorted view of the phenomena itself.

Figure 10: The Antennae Galaxies, where two galaxies are currently merging. The image is a collage of different images, each focusing on a specific aspect to investigate. For example, the pink colours shows where there are hydrogen gas. *Image Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration*

Using the ADD, it is possible to study and classify what a student discerns from a representation, but also how disciplinary proficient the discernment is. This classification can then be used to adapt the teaching to the student's level of discernment. Just because the student says the term 'Force' does not mean they understand everything about the concept of 'Force'. By returning to the same representation several times during the learning process, deeper aspects may be discerned that was not discerned before. Within the social semiotics framework, these aspects are described as present and appresent affordances, where the present affordances are what can be seen or experienced and the appresent affordances are what requires disciplinary knowledge to discern. Appresent affordances (Linder, 2013) requires some interpretation from the students side to discern, often through the use of their disciplinary knowledge, such as combining an image of small coloured dots with the knowledge of space and stars to identify the different stars and their spectra. The ADD is a development the spiral-curriculum created by Bruner (1977), with its focus on going back to the same topic several times to get a deeper understanding of the topic. Each cycle in the spiral-curriculum would correspond to moving up one step in the ADD.

3.5.1 Affordances and Meaning-potential

Affordance is a term that the describes the meaning-potential of a resource. It was introduced by Gibson (1979) as a way of describing what different objects offer different agents that interact with them. A wall offer 'Leaning', 'Hanging' and others as its affordances whereas a floor offers 'Standing', 'Stable' and more. In social semiotics the term affordance is interchangeable with 'meaning-potential' and refers to the meaning that may be discerned from a specific semiotic resource.

Disciplinary Affordances Fredlund et al. (2014) introduced the term 'Disciplinary Affordances' and defines it as: 'the inherent potential of that representation to provide access to disciplinary knowledge'. The resources used within the physics discipline, such as Feynman-diagrams, phase-diagrams, plots and graphs all have some agreed upon disciplinary meaning within the physics discipline. That is the disciplinary affordances that they offer the physics community. A representation with high disciplinary affordance can be seen in fig.11. The figure shows x-ray diffraction intensities in a study done at Lund University.

Pedagogical Affordances Airey and Linder (2015) identified a subset of affordances called Pedagogical Affordances which describes how a resource is used, or what it provides, from a pedagogical perspective in a physics education setting. A resource with pedagogical affordance is created with the intent of being used in education, which can mean that it discards disciplinary information in favour of highlighting a concept or aspect. See fig.12

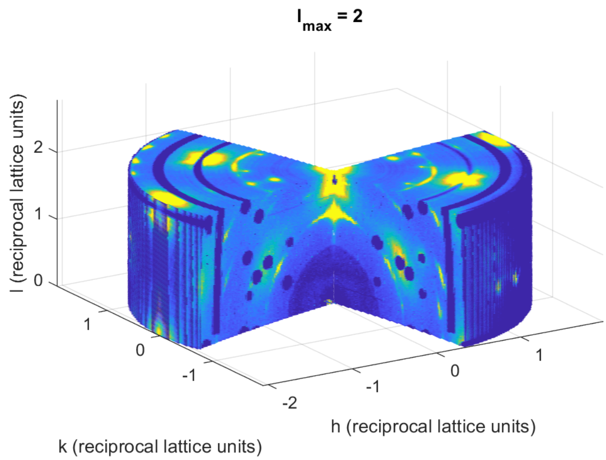


Figure 11: A 3D plot showing the reciprocal space displaying x-ray diffraction intensities. The image showcases a representation with high disciplinary affordance where a great amount of disciplinary knowledge is required to discern disciplinary relevant information. *Source:* Helen Edström, Lund University.

for a resource that have been created for a pedagogical purpose with the simplification of different disciplinary informational aspects. The figure shows two circular bodies and some specifically chosen information which relates to the velocity and forces of the smaller body. The term pedagogical affordances is thoroughly explored by Airey and Eriksson (2019) where they unpack the Hertzsprung-Russell diagram in its disciplinary and pedagogical affordance.

Not all meaning-potential can be discerned at the start. Many meaning-potentials are dependent on a discipline and requires knowledge and experience within the discipline to discern. The meaning-potential that can be discerned by all are classified as present-affordances and can be identified in the 'Non-disciplinary Noticing' section of the ADD hierarchy. Some meaning-potential that requires knowledge within a discipline, such as physics, to discern are appresent and are described in the other steps in the ADD hierarchy (Eriksson et al., 2014). Objects affordances can also be modified on the fly, see fig.13, by placing it a setting or imposing the affordances on the object.

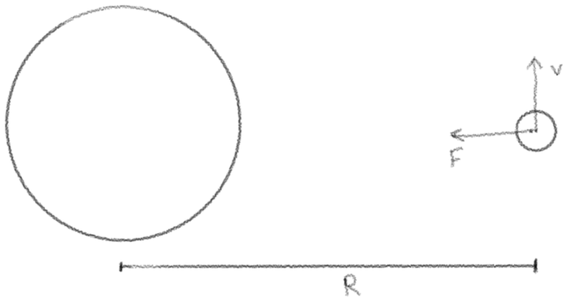


Figure 12: A smaller body is in an orbit around a larger body. The scale of the bodies is not representative of real planets or stars, nor is the distance between them to scale. However, the representation captures the essence of the interaction between the bodies and aims to showcase a specific aspect. The disciplinary information is disregarded to highlight an aspect for pedagogical clarity.

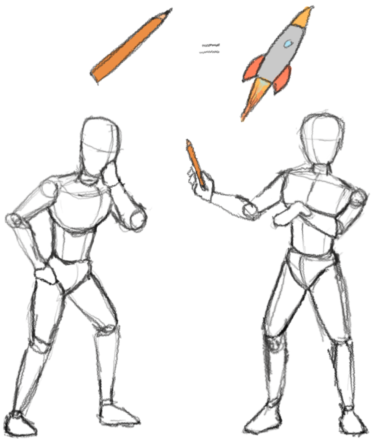


Figure 13: A pens' meaning-making potential can be changed by just saying a simple sentence such as: "Imagine that this pen is a rocket". Others will now discern rocket-related meaning from the pen, such as its direction, shape and movement and relate them to what they know about rockets. This image is also designed in such as way as to increase the discernibility of the pen as a rocket and the aspects of 'discussion', 'explaining' and 'contemplating'. The meaning-making potential can easily be modified by even the slightest suggestion.

My Research

4 My Research

The research presented here aims represent my personal interest of understanding physics, programming and simulations, and theoretical exploration. With my interests it was natural to combine them into the first project: "Programming as a tool for meaning-making in physics education", summarised in papers I and II. The research sparked an interest in learning theories and especially social semiotics and variation theory (sections 3.1 and 3.2), and the results of this interest is presented in papers III and IV and further papers being outlined. The results of the research may serve as guiding principles for educators as they use programming in their classrooms or wishes to use programming outside of the programming classroom as a way to enhance the learning experience of the students. Programming is not intended to replace any existing tool the students use to explore and navigate different physical concepts, but it should be seen as an additional tool to be used by the student, for the student. Below I aim to showcase where my research fits into the larger physics education research field, but also explain the concepts I am interested in and what I have found in my research.

4.1 Programming in Physics Education

Programming has been used as a tool to in physics education before, with varied results, see e.g. Redish and Wilson (1993); Bocconi et al. (2018); Alexandron et al. (2017); Wilensky (1999); Wilson and Redish (1986). However, the arguments for why and how programming should be used have not come from an established learning theory such as social semiotics or variation theory, but mostly 'gut-feeling' and 'this should work'-arguments. Programming is often used as a 'means to an end'-tool in physics education, see the programs NETlogo by Wilensky (1999), MUPPET by Wilson and Redish (1986), or PhET-simulations described by Perkins et al. (2006), by which I mean a tool that is only there to produce a result, the inner workings of the tool itself is not important and can be disregarded. Programming can be seen as a versatile calculator that takes an expression as input and outputs a number or image, where the interesting part is the number or the image. However, as Redish, Papert and others have identified, it is the act of implementing, debugging and modifying the code that offers a learning opportunity. To just treat it as calculator or a means to an end may not create a constructive environment for learning physics and I base this argument on the research done on laboratory work in physics education, see e.g: Watson et al. (1995); Uzezi and Zainab (2017) for studies showing poor student performance based on recipe-style laboratory work. Cooperation as opposed to individual or competitive laboratory work have also been shown to produce better results (Okebukola and Ogunniyi, 1984). Programming should thus be used as a tool for exploration and investigation by students in a cooperative manner when used in physics education research with the intent to further the understanding of different physical concepts. Programming is also versatile and exact in its construction which allows for both qualitative and quantitative explorations of different ideas or concepts. It can also be used as a way of unpacking and highlighting aspects during the implementation and visualisation process. See further exploration of this idea below in section 4.2.1.

4.1.1 Programming and Meaning-Making

Programming provides a tool to investigate and understand different physical phenomena but also a new way to think about the physical concepts or ideas. Computational thinking (e.g. Caballero et al., 2012b; Chabay and Sherwood, 2004), or algorithmic thinking, is the process of analysing a problem and figuring out its sub-components and how they fit together to solve the problem. In papers I and II the workshop was designed to create a particle-based physics engine with the goal to compartmentalise the different components of the simulation into easy-to-understand methods or functions. The students had to subdivide the problem they faced as part of trying to create a program that would solve it. Some of the questions they had to address and answer were:

- How do the particles interact with each other?
- What are their initial values? (temperature, mass, location, velocity...)
- How do we update the simulation between each timestep?
- How do we visualise the simulation?

Each of these questions can be answered by itself, but only when combined together will they produce a functioning simulation. As the student breaks down and answers the different questions, they move through Kolb's learning cycle and have the possibility to learn.

The students then combine the different parts to a larger program, testing and fixing its various kinks, and moves through Kolb's learning cycle ones again, but this time with the whole program in their focal awareness. Thinking of physics in this manner provides a new way of experiencing the act of doing physics. The act of learning physics is conceptualised in a programming-context. I suggest that having to think about each of these questions provides different insights into the physics of the problem and what is needed to solve a physics problem. It is through the act of implementation, fixing errors, analysing the output that a deeper understanding of the physics itself can be obtained. Using programming, the student can create meaning about physical phenomena that they may have struggled to understand without using programming. The code for papers I and II is provided by Svensson (2020).

4.1.2 Coding, Visualisation and Interaction

Programming provides different ways to learn about physical phenomena as they are implemented into a simulation. I have chosen to divide the different ways of interacting with programming in three different categories: *coding*, *visualisation* and *interaction*.

Coding Coding is the act of writing code, an essential act when programming. As the student code, they are performing a transduction, taking the formulas from mathematics to code, making the relationships between different variables or attributes explicit. Nothing is hidden behind 'means to an end' thinking, everything is explicit and the student, in the act of creating a functioning simulation, will become immersed in the code and understand why and how it works. Since the code is a transduction of formulas from the physics discipline, understanding the code itself means that the student also gain and understanding of the formula. The act of implementing the formula into code requires the student to unpack the formula and express it in another semiotic system. This provides a new take on the physics, separate from only using standard formulae and problem solving, but with well defined transformations between the mathematical formulation and the code formulation. In fig.14, two particles interact with each other according to some formula. The formula is unpacked and implemented into code and the result is a force that acts on the particle. By unpacking and implementing the formula the student can gain a deeper understanding of the formulas parts and what the different parts represents.

```
# Defines how a particle interacts with another particle
def interact(self, p):
    l = dist(self.x, self.y, p.x, p.y)
    dx = (self.x - p.x)/(l+0.1)
    dy = (self.y - p.y)/(l+0.1)

    k = 10000
    Fx = dx*(self.rod_length - l)*k
    Fy = dy*(self.rod_length - l)*k

    self.applyForce(Fx, Fy)
```

Figure 14: Example of a method that calculates the force between two particles. The code is written using Python and the Processing IDE. By implementing the code, the formulas used must be unpacked and understood to obtain a functioning program.

Visualisation Many simulations often produce a long string of numbers as its output that may be hard to understand at a first glance. By visualising these numbers on a display, or paper, the relationship between different variables or attributes can be discerned. The evolution of the whole system can also be observed and meaning can be constructed from the discernment of disciplinary relevant aspects. However, programming also provides the student a means to modify the visualisation to their own needs. A student can modify a simulation to showcase a specific attribute to better understand how it evolves and how it is related to the system as a whole. By allowing students to modify and explore the visualisation of their simulation they are free to highlight aspects that they had a hard time discerning, or to highlight attributes that they find interesting. In fig.15 we see different visualisations based on the same underlying data. Each of the different visualisations provide the student with a new aspect to discern, explore and understand.

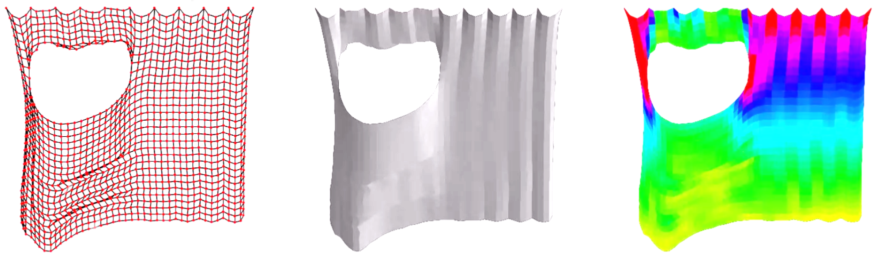


Figure 15: The same simulation is visualised in different ways. Each visualisation affords the student the opportunity to discern different aspects. The left image shows the springs and the particles that is the core of the simulation. The middle image shows a more realistic rendering of the cloth where the shading indicate how the cloth folds. The right image shows the strengths of the internal forces of the cloth. The simulation is not exact, but only meant to showcase the results of coming up with a model, implementing and testing it through the use of programming.

Interaction Interacting with simulations provide a new way of exploring the simulation, similar to the experience of interacting with a physical laboratory setup. By pushing, pulling, adding thermal energy, pressure or other aspects, the simulation will react and adapt and the student may discern new phenomena, or affordances, from the new emergent situation. However, interactions with the simulation are restricted to the peripherals the program supports, such as, mouse and keyboard, game controller, stylus, motion tracking or Virtual Reality Controllers. More research must be conducted on what each peripheral offers in terms of enhancing understanding in a learning environment, but what they all have in common is a way to input data in real time into the simulation. The simulation uses the new data and produces a new result for the student to study. The interactivity of a simulation allows for exploration of the physical phenomena in a dynamic and casual way. The interactivity provides ways to test conceptual ideas within the program that may be hard to program, such as dragging and pulling on a piece of cloth. The specific numbers produced by the interaction may not be interesting, but the dynamics and the emergence of phenomena are what is being explored. In fig.16 we see an example of an interaction between the student and the simulation as the mouse is dragged across the simulation of hanging cloth. The interaction produces a dynamic response from the simulation and allows the student to quickly discover new interesting phenomena that emerges from the implemented formula.

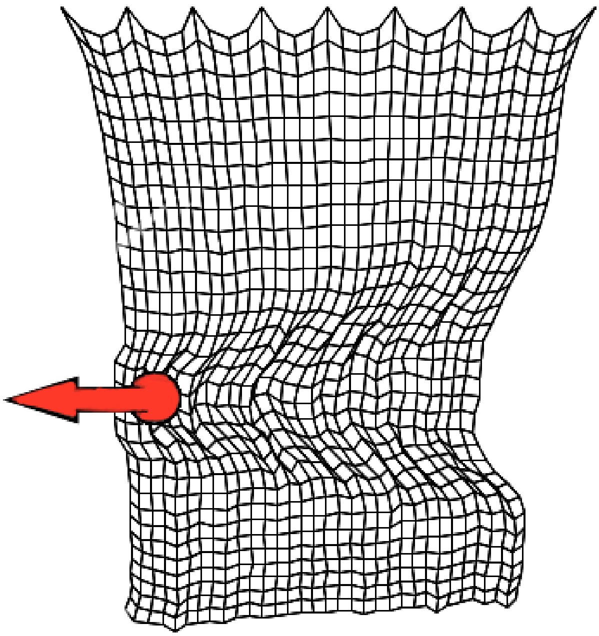


Figure 16: The mouse (red arrow and ball) is dragged across the visualisation of a hanging cloth simulation and exerts a force on the cloth itself. The simulation reacts to the interaction and new dynamics or scenarios can easily be created and observed.

4.2 Semiotic Resources and Transductions

A semiotic resource is any tool, activity or representation used to convey meaning in a specific social group, such as in the physics or physics education research discipline (paraphrased from: Airey and Linder, 2015, p.10). That means that representations are a subgroup of semiotic resources. However, any operation that can be made to the content of a representation, can also be made to a semiotic resource. Semiotic resources can also be constructed from other semiotic resources. A good analogue for a semiotic resource is the concept of a 'system' in physics. A system may just be one atom, or a single electron, which interacts with its environment through some interaction. But a system may also be the whole bio-sphere, or the solar system or even the whole universe. A system may contain many different smaller system that are all contained in the larger system. A semiotic resource can, in the same manner be constructed of smaller semiotic resources from many different semiotic systems. The semiotic resource 'Kinematics - 101' (a fictive course) consists of many different semiotic resources: '$s = vt$', vectors, derivatives, plots, demonstrations, which in turn consists of more semiotic resources. The semiotic system of the semiotic resource 'Kinematics - 101' is 'Lecture' or 'Course' depending on the scope of the learning goals.

By performing a transduction on 'Kinematics - 101' we can move it from the semiotic system 'Lecture' into the semiotic system 'Book' or 'Chapter in book'. Transductions bring with them a number of interesting aspects that are relevant for my research. When a transduction is performed, a number of implicit questions needs to be answered which in turn depends on the semiotic resource itself, but also the context which it is to be used within.

Students in paper I, II, III are all performing transductions when they move from formula to code, or from formula to graph. How they perform this transduction is an indication of how they think about the problem and about their understanding of the different relevant parts of the problem. A student may chose to go a long and elaborate path through many calculations and plots to end up at the relevant understanding, or they may see a short path that only requires a quick manipulation of the formula thanks to their previous knowledge.

Transductions are interesting as they change a semiotic resource from one to another while preserving some disciplinary information. When a function is transduced into a graph, the symbolic information contained in the function is changed into a simple curvy line. Almost all symbols are gone and replaced by a few lines, but the disciplinary relevant information is still there, ready to be discerned. By looking at how students transduce, or even produce, semiotic resources we can observe how they preserve disciplinary relevant information, or how they do not. We can gauge which aspects the student deem relevant to the problem and we may get a better understanding of what the students discern and what their relevance structure is. Once this is known, an informed intervention can be performed to help scaffold the student in their meaning-making efforts.

4.2.1 Programming as a Transductive Link Between Semiotic Systems

See paper IV for a more complete description of what a transductive link entails. A transductive link is a semiotic system that aides in the transduction process. The initial semiotic system and the final semiotic system is separate from the semiotic system of the transductive link. See fig.17 for an example of using programming to perform a transduction. The transduction itself does not need to be done using programming, it can be done on paper using a pen and mathematical knowledge, but using programming provides a new way of performing the transduction.

Figure 17: The function $f(x) = y$ is transduced into a graph using programming as the transductive link. Depending on how programming is used, the path to the final image may be hard to follow or straight forward for the student to understand.

The type of semiotic system used as the transductive link will affect how the transduction is carried out and will introduce or remove information from the system specific to that semiotic system's properties. Programming provides exact and implicit control of the transduction process. Every step of the transduction requires the student to unpack the specific semiotic resource they are transducing to understand its parts and how they are connected to each other. Using programming as the transductive link will provide unprecedented control of the transduction with the implicit necessity of unpacking and understanding the semiotic resource itself.

Several transductive links can be coupled together into a transductive chain, where each link in the chain is a transduction. In fig.17 we make the graph into a transductive link that links programming to a real world prediction. Perhaps predicting where the ball will land. The chain would then be: 'Formula' $\rightarrow$ 'Programming' $\rightarrow$ 'Graph' $\rightarrow$ 'Hypothesis/Experiment'.

4.2.2 Affordances and Semiotic Resources

It is possible to compare different semiotic resources to each other by looking at semiotic resources in terms of their affordances. We may determine what a semiotic resource, such as the figure in fig.13, affords for the physics discipline but also what it affords for the context and the setting it is in. Using this knowledge, we can contrast and compare it to other semiotic resources by comparing the different semiotic resources affordances with each other. This work is currently only theoretical, but it provides a language for talking about what happens when we interact with semiotic resources and how different semiotic resources can be combined, divided, modified or compared. By studying the disciplinary relevant aspects we would like students to discern, we could construct new semiotic resources that affords the specific aspects. This idea could be used to construct or to unpack different semiotic resources to ensure a learning environment where the student has a good chance of discerning the disciplinary relevant aspects.

4.3 Where my research fits in PER

The work presented in I, II and IV constitutes my research interest and encompasses both theoretical analysis, empirical work and practical applications of learning theories. Social semiotics have been extended significantly by Professor Cedric Linder's Physics Education Research Group at Uppsala University in Sweden and my work is very much based on their work. I have taken the ideas of social semiotics and applied them to the idea of using programming as a tool to understand physics. Programming in physics education has been studied before, see for example, Redish and Wilson (1993); Caballero et al. (2014); Aiken et al. (2013), but not using the newly developed framework of social semiotics. The results from paper I and II provides a practical insight into using programming in physics education, but also investigate how to apply this newly developed theoretical framework in a novel way. Paper III is tangential to my research and is not part of my main research area; the paper expands upon the knowledge around relevance structure and disciplinary relevant aspects and what students discern.

Methodology

5 Methodology

A qualitative approach was taken to inform the setup, collection and analysis of data throughout the research in all papers presented in this thesis. Since this research aims to observe student understanding and learning, and what learning environment and aspects of those learning environments provide for learning and understanding, a qualitative approach is required to understand how the new learning experience affects the students' understanding. Most of the research is inspired by grounded theory (Glaser and Strauss, 1967) but situated within the theoretical frameworks of social semiotics and variation theory. Social semiotics and variation theory provides frameworks to describe what is observed, and meaning to the patterns and concepts that emerge from the grounded theory approach.

Below is a description of how I use the different theoretical frameworks described in section 3 in the construction of the data collection and during the analysis of the data.

5.1 Grounded Theory

Grounded theory (Glaser and Strauss, 1967) served as the underlying methodology as the research project was being developed and the analysis was starting up. Grounded theory starts without a theory and builds a theory based on the observations and analysis that are done from the collected data. In papers I and II, grounded theory was combined with social semiotics and variation theory to create an understanding of how using programming as a tool for meaning-making could enhance the learning experience for the physics discipline for upper secondary education students. The construction of the data collection method (the workshop and interviews) was heavily influenced by social semiotics and variation theory but it was also designed with the idea to capture as much varied data as possible to allow for a grounded theory approach in the analysis. Social semiotics and variation theory were used as the descriptive theories and grounded theory was used as the analytical tool used in the investigation.

After applying grounded theory, by constructing and connecting coded segments of interviews and interesting aspects of the workshop, some interesting ideas about the usage of programming in physics education emerged. These ideas were then contextualised using social semiotics and variation theory by identifying different semiotic resources and different types of variation that were used by the students, but also by me (as the lecturer) in the construction of the learning experience and environment. The context of the learning environment was always related to programming, but aimed to used different semiotic systems and different resources to provide a varied learning experience. Some of the different semiotic systems that were used during the data collection for papers I and II, were: 'Gestures', 'Text', 'Code', 'Speech' with many more. The students were placed in an active learning environment where they were encouraged to discuss and come up with solutions in smaller groups. The idea behind variation theory was provided to the students to fully use as they varied different variables or implementations to test different ideas or to investigate new scenarios.

5.2 Phenomenography and variation theory

A phenomenographic approach (Marton and Booth, 1997) to the design of the interviews and the interview questions were used in papers I, II and IV. The aim of the interviews and the studies was to extract many different views and experiences from the interviewed participants by allowing for open ended questions and for the ability for the interviewer to follow up and explore different answers. However, phenomenography was not used in the analysis of the interviews as we did not aim to create a classification of experiences, but to observe students in the process of learning and what aspects affected their learning, with a special focus on the programming aspect of the learning experience. The phenomenographic approach is thus not used except as a guide for the construction of the pilot study. For a detailed presentation of phenomenography, see Marton and Booth (1997).

To facilitate different ways of experiencing learning in papers I and II, variation theory (Marton and Booth, 1997; Lo, 2012a; Ingerman et al., 2009) was used to highlight different aspects of programming as a tool for meaning-making for the students. By showcasing variation in the variables introduced and by allowing the students to vary aspects as the program develops, a greater understanding of each variable or aspect of the program can be gained. Variation theory informed the pace of the workshop in papers I and II since it was needed to plan for the time when the participants could explore the code/visualisation/interaction of the program. The aim of the workshop was not to produce functional or accurate simulations, but to explore programming as a tool and its potential use in physics education.

5.3 Transduction and Multimodality

As part of the workshop in papers I and II, transductions (Volkwyn et al., 2019; Stein, 2007; Kress et al., 2014) and the theory of multimodality (Bezemer and Kress, 2008; Kress et al., 2014) was used to ensure a good learning environment for the students. The aim of using these ideas was to provide a varied, but structured, learning experience for the student that would allow the researchers to observe different phenomena associated with the learning process and the use of programming in that process. Powerpoints, formulas, gestures, text, live-coding, animations and images of the different concepts were used to represent each concept or idea, using the power of multimodality and transduction. The idea of transductions are explored further in paper IV through the concept of a transductive link.

5.4 Data Collection

For papers I, II and IV it was necessary to collect data in the form of video and audio recordings. The information that was in focus for each study was extensively discussed with the other researchers at NRCF and the data collections sessions were designed to provide opportunity to answer specific questions, or to observe students in specific scenarios. The data collected is in the form of images and sound from students and teachers, which means that we are required to handle personal data. The data collection must follow the General Data Protection Regulation (GDPR) (European Commission, 2018), a newly implement EU regulation for the protection of personal data and personal rights with respect to the data.

Below is description of some important steps in the data collection process and how they are regulated by the GDPR. It should also be noted that this research was done during the implementation of the GDPR and some data collection session were performed before the GDPR came into effect and some data collection session were performed after GDPR came into effect. Some data collection protocols have thus been updated retro-actively. Which means that the stored data will handled as if the participants had signed a consent form that complied with the GDPR-rules.

5.4.1 Personal experience with handling personal data

Since I had no prior experience with handling or collecting personal data for research purposes, an intense period of studying the laws and regulations was required to ensure compliance with the GDPR (see below) and Swedish law. This has taken up a fair bit of time and has resulted in an emerging cooperation with the library in the physics department to streamline the data handling and archiving process. I have devoted time to developing the consent form, a data management plan and a workflow for further data collection sessions. Everything developed for data collection and handling is being tested and evaluated and will be modified in the future.

5.4.2 GDPR

The General Data Protection Regulation (GDPR) (European Commission, 2018) aims to provide comprehensive regulation of how data, and specifically personal data, should be handled and protected in a digital age. GDPR focuses on the rights of the individual and the individual's ownership of their own personal data. Two of the rights that the GDPR stipulates, that also affect how we collect and handle data, are:

- The right to data portability:
    - All gathered data should be transferable to the data subject in commonly used formats and the data subject can use their data for any purpose.
- The right to be forgotten:
    - All data that can be linked to the data subject by the researcher, (not anonymised or published anonymised data), must be destroyed if the data subject requests it. That data can no longer be used in the research.

These rights ensures that the data must be kept in a organised state and that a proper workflow for handling the different situations is in place. This workflow did not exist before the studies in paper I and II, but has since been developed, by me, to ensure compliance with the GDPR at the NRCF. More information about this can be found in the consent forms in the appendix 11.4.

5.4.3 Recruiting the participants

GDPR (article 7) stipulates that any participant of a research study must willingly enter into the research. They must be fully aware of the research itself, what their role is in the research, any risks associated with taking part in the research, what the research and/or their data will be used for and their rights related to their own data. This is taken care of in the consent forms, see appendix 11.4.

Papers I and II The participants for papers I and II were recruited by visiting their class in their school to promote research into understanding learning physics. A few students had already expressed interest in the study when they took part in a physics competition at Lund University and met me. Many in the class were interested and signed up, but only six students remained interested at the start of the workshop, about two months after the visit to their class. At the workshop they were given the consent form and an introduction to what the research entailed and their part in the research. The workshop took place at Vattenhallen Science Centre at Lund University in southern Sweden. The science centre was chosen as the location since it offered a setting different than their usual school or lecture hall. I have also performed similar workshops at the science centre and have access to the facilities.

An ongoing study, studying teachers potential usage of programming as a means for meaning-making in physics education, recruited participants online from a Facebook-group. The Facebook-group is called 'Fysikundervisning' (eng: 'Physics Teaching') and is created for physics teachers, and interested individuals, to discuss physics and educational challenges or new ideas in physics education. The group is curated by The National Resource Centre for Physics Education (NRCF) at Lund University which is also the location where this research is being conducted. The participants were provided with a digital version of the consent form and the research was thoroughly explained in an online-meeting using the Zoom-software. The participants were required to hand in a signed paper version of the consent form at one of the two meet-ups in Lund that took place during the data collection process. See appendix 11.4 for the consent forms used in the research.

Paper III The participants for paper IV were recruited in the classroom where all students were asked to participate in an interview about the exam. The participants signed up and an interview time was agreed upon. Before the interview began, the research was explained to them and they signed the consent form seen in appendix 11.4.

5.4.4 Audio and Video recordings

Video and audio recordings were essential for gathering data for papers I, II and III. The videos were recorded by newly bought GoPro Hero 6 GoPro Inc (2019) cameras. The GoPros were chosen since they allowed for great mobility and ability to fasten them on equipment or bodies to provide camera angles that would be hard with larger cameras. The cameras were also chosen based on recommendations from other researchers in the PER field that recommended them because of their sound quality. However, for the papers presented here, the cameras were mostly used as static cameras but in other research conducted at the NRCF the mobility of the cameras has been used to capture student learning.

The audio was captured using several Olympus WS-852 Digital Voice Recorder-devices. The GoPro cameras can record audio and the Olympus-microphones were used as backups if the cameras were to fail during a recording session. In situations were audio from the cameras were distorted or hard to hear, audio from the microphones were used to fill in the missing information.

5.4.5 Consent Form

In the research presented in this thesis, two different consent forms have been used. One before GDPR came into effect and one after GDPR was implemented. Here follows a short description of the different consent forms, see appendix 11.4 for the consent forms used in papers I, II and IV. The study performed in paper I and II took place before and after the 25 of May 2018 when the GDPR was activated. The participants signed a consent form that did not conform with the GDPR before the 25 of May. However, the consent form has been updated after the fact and the participants were informed of the changes during the last session of the workshop, but no new consent had to be obtained from the participants. We, as researchers, follow the updated consent form as it describes the handling of the data, who gets to analyse it and how the data is weeded out and potentially published. Paper III, and the current ongoing study with teachers perspectives, uses the updated consent form.

5.4.6 Data Management Plan

The notion of a Data Management Plan (DMP) has not been in focus in the Physics Education Research field at the NRCF, nor in many other fields at Lund University, this is mainly due to the low amount of data collected in the physics education research field before the studies presented in papers I, II and III. A larger push for better data management is in effect (as of 2019) at Lund University and the NRCF, that aims to provide a well structured and useful way of handling, archiving and publishing data. A DMP for physics education research is being developed by Kim Svensson at the NRCF, that will be based on Lund University's own DMP that is also in development. There is no DMP for the research published in this thesis. However, the data and the handling of the data is defined by the consent forms and the GDPR. A DMP would aim to define the responsibility, handling and the type of data that is being collected. An example of questions the DMP aims to answer are; "How is the data stored?", "Who is responsible for accuracy and backups of the data?" and more. A DMP also restricts the scope and budget of a project and helps to narrow down the focus on the research questions. The DMP also serves as a checklist to go through as the project progresses to ensure that each step is done properly and that the project stays on track. A detailed DMP is expected to have been developed and tested and in use by the time my doctorate thesis is complete and will be included in it.

5.4.7 Data Storage and Archiving

The recorded data will be stored in three separate Solid State Drives (SSD): One SSD where the raw data is stored and can be analysed and manipulated, one SSD for just the raw-data with no manipulation, it also contains the consent forms and other information about the project and one SSD for backup. All the data is stored locally at Lund University. Data archiving is planned, but the details are still being explored, but a cooperation with the university library is expected to ensure compliance with Swedish law.

5.4.8 Data Publishing

No data that can be used to identify any participant in papers I, II and III will ever be published. The participants can choose to disclose that they participated in the study, but the researchers will never divulge who the participants were that took part in the studies. Data that have been anonymised can be used in publications such as select quotes, drawings or images created by the participants.

I have begun to work on a workflow and a DMP that would ensure the possibility to publish fully coded and anonymised transcripts in online repositories. The data could then by used by other researchers in similar work, and larger studies using data from many data collection settings could be done in the future. This work is still in the exploratory stage and the final product may not be possible. However, the anonymised data presented in papers I, II and IV will not be fully published since this is not part of the consent forms used in the studies.

5.4.9 Data Erasure

The raw-data will not be erased, but archived at the end 2022 when the different projects come to an end. The responsibility for the data erasure will be transferred to the archive that handles the data and performed when the archiving period has expired.

5.5 Trustworthiness

The trustworthiness of the work presented in this thesis follows the categories created by Guba and Lincoln (1982). Guba and Lincoln compared naturalistic research with rationalistic research to determine if the criteria for good rationalistic research could be applied to naturalistic research and found that it could not. They proposed a new set of categories that mimic the rationalistic ones, but differ in their implementation. The categories that Guba and Lincoln suggests are; credibility, transferability, dependability and confirmability and together they cover the different aspects that a scientific study should exhibit. The study should be credible; it should be conducted by experts, or with expert guidance, with expert knowledge within the field and with knowledge of the methods used in the collection and the analysis of the data. An analysis of how the methods, analysis or results can be transferred outside of the work should be performed and presented (see below) and detail how the work, or what parts of the work, can be transferred outside of the work itself. Dependability is a statement on how dependable the method, analysis or results are which were used in the work. This is done by referencing older work or by validating new methods with older published results. Confirmability is the ability to confirm the the results from the work, and if this is possible or even desirable. In paper IV, the results are theoretical and can easily be confirmed by others using the theoretical frameworks. However, paper I and II uses quotes to reinforce the analytical results, the specific results will be hard to reproduce since the cohort is small.

Credibility The credibility of the work shown in the papers presented here comes from the fact that each interesting talking point is presented in the papers with quotes from the interviews. Paper I have also been reviewed by the participants to ensure that their views or meaning have not been distorted. The analysis process of all the papers has been a team effort by the people at NRCF which ensures that personal biases in my interpretation is kept to a minimum. The theories used in the papers are relatively new but they are built upon the data and analysis done before, they are built upon empirical evidence and lends credibility to the analysis and methods used. The use of social semiotics, variation theory, the concept of affordances, grounded theory and some phenomenography ensures a triangulation effect that tells us that the aspect under scrutiny is not a fiction that emerged by the quirks of one theory.

Transferability The conclusions from papers I, II and III are theoretical and observational and should not be assumed to apply to all scenarios or students. The observations made in the studies, however, should be taken into consideration when considering using programming in physics education (papers I and II) or teaching about circular motion (paper III). Paper II is a theoretical analysis of programming in a physics education setting using social semiotics, variation theory and affordances and should be seen as an attempt to apply the ideas found within the different theoretical frameworks on a new learning environment. The method for analysis and the analysis of programming using the frameworks can and should be used in future research or application of the results. However, the data collection process of papers I and II are designed to create a best-case scenario for the specific data we were looking for. The results from papers III and IV can be transferred to their respective usages in education, specifically circular motion and the usage of different transductive links in education. Paper III should be seen as an added data-point to be used to understand students' difficulty when learning about circular motion and paper IV should be seen as providing a language for talking about different transductions or transductive processes.

Dependability Papers I and II can be repeated using the code and the same workshop but the main difference will be the students and how their interest or personality will affect how they interact with the physics and programming. The selection process for the students were designed to get students already interested in physics and new ways of understanding or learning physics. Thus, the results from papers I and II should be seen as theoretical and requires further research to test in active classrooms. More research is currently being conducted by me on this aspect where a select group of interested teachers are trying out the same type of programming in their secondary education physics classroom in different schools in Sweden. However, the analysis and the data collection process for papers I, II and III were carried out by experienced researchers at Lund University and extensively discussed in their intent and structure to ensure good quality data. The data collection and methods for paper I and II were also discussed with experienced researchers at Uppsala University to avoid systematic biases.

Confirmability Papers I and II present results that are mostly theoretical in nature. The results from the data collection should be seen as independent data-points that require more research to even have anything to confirm, except to analyse and compare with theoretical phenomena. Paper IV is theoretical and can be confirmed by similar theoretical analysis using the same, or similar, theoretical frameworks.

Analysis

6 Analysis

Each paper presented in this thesis has undergone slightly different, but related, analytical processes using the theoretical frameworks presented in chapter 3. Below is a description of the analysis for each paper. More information can always be found within each paper.

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

The paper itself focuses on the construction of the data collection process and some preliminary data from said data collection. The methods described in chapter 5 were used in the creation of the data collection. The data analysis took a qualitative approach based in grounded theory. The interviews were transcribed and quotes that highlighted aspects that corresponded to anything related to the research questions were extracted. The quotes and research questions were discussed at NRCF with the intent to extract programming's main aspects and how they differ from standard physics education. The aspects were then related to ideas within social semiotics and variation theory. The information gathered in the study informed the analysis of paper II and the design of further projects related to using programming as a tool for meaning-making. Relevant quotations and learning experiences were identified through discussions at Lund University and Uppsala University with experts within the physics education research field. The excerpts and learning experiences were then explored or explained using social semiotics and variation theory. Phenomenography played a role in the first iteration of the analysis and some of the perceived learning experiences identified by the grounded theory process were used as the basis for discussions and the social semiotics analysis. Social semiotics provided a base to begin the analysis of the different semiotic resources the student used, but also what semiotic resources they produced using programming. This analysis also used transductions and translations from the multimodality framework as a basis for describing the way the students used programming.

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

Social semiotics and variation theory are used to analyse programming as a semiotic system to be used in physics education. Special focus is given to coding, visualising and interacting with the simulation. These aspects are described using social semiotics with a strong use of transductions and modifications of semiotic resources. The data from paper I serves as a data-set to compare the theoretical predictions obtained from the analysis. Social semiotics offers the lens of semiotic resources to study programming as a transductive link and a modifier/creator of different semiotic resources. The observations from paper I served as a guide for the analysis and programmings important categories were identified: 'programming as a transductive link', 'programmings' feedback loop' and 'to make formulas move'. The process involved many iterations and discussions with disciplinary experts at Lund University and Uppsala University.

6.3 Paper III: Students making sense of motion in a vertical roller coaster loop

As I was a co-author, not main author, my role in the analysis was less involved than in papers I, II and III. However, the analysis took a grounded theory approach where disciplinary relevant concepts or learning phenomena were identified in the students discussions. The aim of the study was to discover what the students thought about the concept of circular motion and what their conceptual problems may be. Using previous work at the NRCF studying students use of semiotic resources as they tackle problems related to circular motion, different disciplinary relevant aspects were observed in the recorded interview. The analysis focused on understanding the students relevance structure and compare what the student find relevant to what the discipline find relevant to solving circular motion based physics problems.

6.4 Paper IV: The concept of a Transductive Link

The term "transductive link" was first used in 'Multiple Representations in Physics Education', chapter 5, by Airey and Linder (2017) and in paper I. The term has been used before in spam detection filters and in machine learning settings, see Zhou et al. (2007), but not in an educational research setting. The concept of a transductive link is expanded upon and explained in the context of social semiotics and its role in the transduction process. Data from paper I was used as examples of different transductive links and how they affect the transduction process. The idea of a "transductive chain" emerges as a natural extension of the concept of a "transductive link" were several links are connected. The analysis is purely theoretical with a few hypothetical examples to highlight the concept in a context.

Results

7 Main Results of research papers

Below is a summary of the results for each research paper presented in this thesis.

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

The paper goes through the construction of a workshop with the intent to gather data regarding students experience of using programming as a tool for meaning-making in a physics education context. The following results were found in the pilot study outlined in the paper:

- Interested students can go from knowing no programming to creating 2D particle based physics simulations within four workshop sessions, each about two hours long. However, only students that had prior basic knowledge of programming were able to implement their own ideas or modify the simulation without help from the lecturer.
- Students identified the potential of using programming as a tool for meaning-making in physics education as part of their own learning process.
- Students modified the visualisation of the programs to create new representations that better afford what the student wishes to discern.
- Students specifically commented that the ability to 'see the formula in action' was different from their standard physics education and that you don't solve problems with programming, instead you create something.

The programming language was Python (van Rossum, 1995) in the Processing IDE (Fry et al., 2019) which is a high level Object Oriented Programming Language in a development environment that is designed for rapid prototyping and the visual arts. The students appreciated the ability to visualise aspects of the simulation in a window and to make moving animations. The fascination of the student of being able to visualise something on the screen has also been seen by the teachers in the ongoing study.

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

This paper focuses on theoretical predictions based on a theoretical analysis of programming as means for meaning-making in physics education using the lens of social semiotics and variation theory. The predictions made by theory were:

- Potential for a positive feedback loop: As the student explores their program, either by changing the code or by interacting with it, they may discern excepted or unexpected behaviour and adjust their program to fix or expand it. This process can start over and over again, providing a feedback loop for the students to use in their learning process.
- Variation Theory potential: Programming offers an unprecedented potential to use variation theory in a very quantified manner. By varying single variables, it is possible to discern its effects on the system and how it differs from other variables in the system.
- Transductive Link: Transductions have been found to be important and helpful in the learning process. Programming acts as a stepping stone between two different semiotic systems when a transduction is made. Programming acts as a transductive link between the two semiotic systems, which means that it is through programming that the transduction takes part.

Social semiotics and variation theory provided tools and a language for analysing programming. The ability to vary, create and move between different representations using programming is well explained by the ideas presented by the semiotic resources and the variation of aspects from the theoretical frameworks.

7.3 Paper III: Students making sense of motion in a vertical roller coaster loop

The study aimed to probe students understanding of disciplinary relevant aspects around the concept of circular motion and to observe students' related relevance structure. The problem discussed required students to know and apply

1. Newton's second law

2. The expression v^2/r for centripetal acceleration

3. The vector nature of force and acceleration

4. The relation between potential and kinetic energy.

Many studies of circular motion involve only a subset of these aspects. The focus group discussions showed that, although students were well acquainted with the relevant physics, they had problems keeping all aspects in their relevance structure at the same time. However only a small amount of scaffolding/intervention was required to remind them of omitted aspects.

The students were shown a different representation of the problem using Augmented Reality (AR). An animation of a car going around a vertical-loop was superimposed on top of a physical paper with the text and image of an example of the problem, using a modern smartphone. Some students exclaimed that it offered different information than what was provided in the text and would have prompted them to attack the problem differently. They said that if they had seen the car move, they would not assume that the car could be at rest at the top of the loop, but they also said that a roller-coaster-train could be at rest since it could hang on to the rails. This highlights the importance of being able to discern the DRAs of the problem and how easy it is to modify the discernibility of different DRAs using different representations.

7.4 Paper iv: The concept of a Transductive Link

The paper, as the title suggests, introduces the concept of a transductive link in the context of social semiotics and its semiotic systems and semiotic resource. The concept emerged as an idea in paper Airey and Linder (2017) and was used in paper i but it had not been thoroughly explored or defined. This paper serves to expand on the idea to a fully fledged concept that can be used as an important puzzle piece in the further construction of social semiotics as a theoretical framework. A transductive link is an semiotic system that aides in the transduction between two different semiotic systems with the ability to link several transductive links together to create a transductive chain. The transductive link that is chosen imparts its own touch on the transduction process and will affect how the new semiotic resource is constructed. Different transductive links, or chains, are useful in different settings with different audiences. The paper is purely theoretical and only aims to showcase the idea of a transductive link.

Conclusion

8 Conclusions and Future Research

Below are the conclusions for papers I, II, III and IV and suggestions for future research into the areas explored in the papers. This chapter is divided into two parts: The first part addresses my research about programming as a tool for meaning-making and the findings and suggestions for future research into this area. The second part addresses the analysis of semiotic resources and their dynamics, my present findings and, what research is currently being done and planned for.

8.1 Programming as a tool for meaning-making

This whole licentiate thesis began with the idea: "I have found that I understand concepts better if I implement them into code, I wonder if this can used by others in physics education". The aim of paper I was to observe if students could use programming as a tool in their physics learning process, and how it turned out that they could and that they saw the potential to use programming on their own for learning or understanding physics concepts. This naturally developed into 'how'-questions: "How does programming help in the learning process?" and "How do we analyse programming from a learning theory perspective?". Paper II aims to answer these questions since it analyses programming from a social semiotics and variation theory perspective to understand which aspects of programming are beneficial for learning physics. The following aspects of programming were found to be important and were observed while the students were implementing and discussing their models:

- Transduction: Moving between different semiotic systems, or modes, such as: between a graph and a function or a formula; students implemented text-book formulas, or developed their own formulas, into code. The code was run and created a graphical representation of the phenomena based on the formula. As such, the act of programming work as a transductive link for the student between the graphical representation and the text-book formula of the physical concept.

- Instant feedback and iteration: Thanks to programmings ability to quickly execute complex commands and to display them on the screen, the student gets instant feedback on their changes and ideas. This provides an opportunity for an iterative approach to solving the problem at hand by solving and testing parts of the solution separately.

- Interactivity: The student may interact with the code or the graphical representation to quickly test new hypothesis or to open up new dimensions of variation to explore. The interactivity that programming provides is only seen in the real world, however, the real world lacks the ability to decouple physics phenomena from another. Meaning that it is hard to isolate different physical aspects from each other in a real world laboratory, but it is easy in a programming environment.

The initial research began with the hypothesis that learning physics could be enhanced by dividing programming into three separate functions: Visualisation, Coding and Interaction; these categories presented our hypothesis of which aspects of programming plays a major role for its use as a tool for meaning-making. The three aspects have now been transformed into the three aspects seen above and in fig.18. The interaction-aspect largely remains the same, while the visualisation and coding aspects have shifted into the transduction and iteration aspects. Transduction requires the unpacking of formulas or ideas and hence guides the visualisation. Iteration is the aspect of change in both the code and the visualisation. A change in the code, or the visualisation, brings with it a possibility to discern and explore different relevant aspects of the simulation.

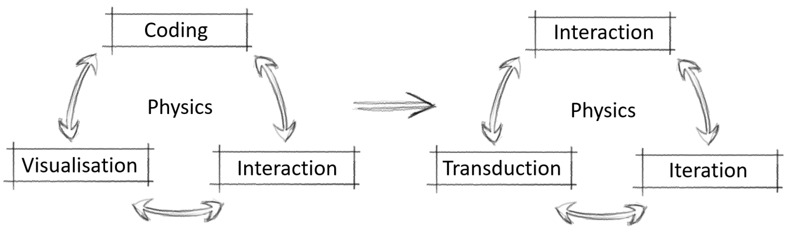


Figure 18: The original idea regarding the use of programming to enhance learning physics was to divide it into three separate aspects: Visualisation, Interaction and Coding. The analysis have evolved these ideas into the new categories: Transduction, Iteration and Interaction. Coding and Visualisation have been combined and divided into the categories of Transduction and Iteration since they contain the important parts of the aspects.

8.1.1 Further research

Students are capable of using programming as a tool to understand physics. The next step would be to test this type of programming in a real classroom setting and determine if it is viable or if modifications need to be introduced to the process. A study looking at teachers experience using this type of programming in their classroom is currently being conducted (fall 2019) and the preliminary results looks promising. However, the analysis is ongoing and thus beyond the scope of this thesis.

8.2 Semiotic Resources Analysis

The analysis of semiotic resources and the dynamics of semiotic resources is ongoing and paper IV present the first preliminary results of this research. The final semiotic resource after a transduction is tied to how that transduction was performed. If a graph is drawn by a computer or by hand will affect how it looks and what specific affordances may be discerned from it. In that case, the transductive link will determine the possible learning opportunities of the action.

RQ2 and RQ3 deals with the analysis and description of semiotic resources and therefor their answers are linked. By describing semiotic resources in terms of their affordances, and how a modification of the semiotic resource is equal to a change in its affordances, we can begin to understand different types of semiotic resources and different types of modifications. In paper III, an animation of a car in a vertical loop was shown to the students which triggered new discernment of different affordances, compared to a static image of the same physical situation. The affordances that were present in the still-image and in the animation were possibly very similar, but differs in certain important disciplinary relevant aspects and in the ease by which these DRAs were discernible by the students. By explicitly showing the car moving, we increased that specific affordances', and hence DRAs', discernibility. This was to be compared by the task at the exam, where that specific affordance was still presented explicitly in the text + image of the problem. However, the students did not easily discern this as uniform motion and could not combine all DRAs in their relevance structure and thus failed to solve the problem. We thus found that the simulation was a critical contribution and made it possible for the students to discern this particular DRA.

8.2.1 Further research

Further research into the dynamics of semiotic resources will involve studying different types of modification and trying to describe how students discernment change over time as they interact with many different semiotic resources. A way of measuring or determining the different affordances of a semiotic resource is required to be able to make predictions for real world predictions and applications.

Summary

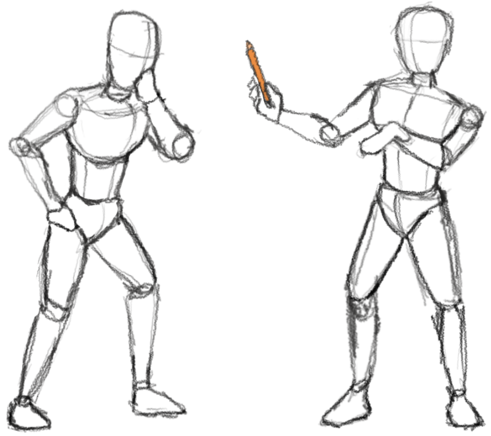
9 Summary of my research

The idea that programming could be used to understand physical concepts through the act of implementing and exploring code initiated the study seen in papers I and II. The results from these papers allowed me to answer RQ1 about how programming may be used as a tool for enhancing meaning-making in physics education using the ideas from social semiotics and variation theory. In order to analyse the students' experiences as they used programming to create physics simulations by constructing a particle-based physics-engine in Python, I included the concept of affordances together with the theoretical frameworks mentioned above. The students were able to construct their own conceptual models of both a hanging cloth and a two-dimensional heat diffusion simulation, both implemented with the guidance of the lecturer/researcher. While implementing different models the students were encouraged to vary different variables of the simulations to test how these affected different physical aspects of the simulation. Variation theory provided a guiding principle when exploring and understanding different aspects of the code and, by extension, the physical phenomena. The students modified the visualisation of the simulation to highlight different aspects, or just to reduce extraneous load that may have hindered discernment of other aspects the student find relevant or compelling. By looking at this phenomena, using the concept of affordances and disciplinary discernment, it was possible to describe the students' actions as a way of increasing the discernibility of specific affordances (DRAs) of the semiotic resource. The student-created semiotic resources provided opportunities for the student to modify and interact with it, by opening up dimensions of variations based on their own desire to explore different concepts or ideas.

These findings lead directly into RQ2 about how affordances can be used to compare student-created semiotic resources with each other. The concept of affordances provide a strong candidate as a theoretical framework for meaningful and qualitative comparison between semiotic resources with respect to learning. From variation theory, we know that discernment is required for learning, and affordances are the discernible aspects of a semiotic resource. By changing the semiotic resource, we modify the discernibility of different affordances, and by doing so change the learning opportunities. Identifying the salient disciplinary affordances of semiotic resources then allow us to compare its affordances with the affordances of modified or other semiotic resources.

The modification of a semiotic resource changes its affordances, however how the modification changes the affordances are unclear. In paper IV I begin to analyse this problem and identify the concept of a transductive link as an important aspect in the modification process. This is the first step towards answering RQ3 which addresses how the modifications of a semiotic resource affects the affordances of it. Further research into this question aims to study what a modification actually means by modelling a semiotic resource in terms of its relevant affordances.

The title of this thesis; "This pen is a rocket", is the latest development of my research into modifications of semiotic resources. By just stating "This pen is a rocket" new affordances will be discerned from the combined system of 'Pen + Statement' than would be discerned from just the system 'Pen' by itself. We can describe this modification as an increase in the 'Rocket'-related affordances of the 'Pen'. The statement acts upon the 'Pen' and modifies the discernible affordances to increase the possibility to discern them. See fig.19 for a representation of the title.



"This pen is a rocket" - A simple statement can modify what a person discerns from simple objects or resources.

References

10 References

AAPT Undergraduate Curriculum Task Force (2016). *AAPT Recommendations for Computational Physics in the Undergraduate Physics Curriculum*. Retrived from `https://www.aapt.org/Resources/upload/AAPT_UCTF_CompPhysReport_final_B.pdf`.

Abelson, H. and DiSessa, A. A. (1986). *Turtle Geometry: The Computer as a Medium for Exploring Mathematics*. Artificial Intelligence Series. AAAI Press.

Aiken, J. M., Caballero, M. D., Douglas, S. S., Burk, J. B., Scanlon, E. M., Thoms, B. D., and Schatz, M. F. (2013). Understanding Student Computational Thinking with Computational Modeling. *2012 Physics Education Research Conference*, pages 46–49.

Airey, J. and Eriksson, U. (2019). Unpacking the Hertzsprung-Russell Diagram: A Social Semiotic Analysis of the Disciplinary and Pedagogical Affordances of a Central Resource in Astronomy. *Designs for Learning*, 11(1):99–107.

Airey, J. and Linder, C. (2015). Social Semiotics in University Physics Education: Leveraging critical constellations of disciplinary representations. *11th conference of the European Science Education Research Association August 31 - September 4, 2015, Helsinki, Finland*.

Airey, J. and Linder, C. (2016). Teaching and learning in university physics: A social semiotic approach. *The 8th International Conference on Multimodality (8ICOM), 6-9 Dec 2016, University of Cape Town, Cape Town, South Africa*.

Airey, J. and Linder, C. (2017). Social semiotics in university physics education. In Treagust, D. F., Duit, R., and Fischer, H., editors, *Multiple Representations in Physics Education*, volume 10, pages 95–122. Springer.

Alexandron, G., Armoni, M., Gordon, M., and Harel, D. (2017). Teaching Scenario-Based Programming: An Additional Paradigm for the High School Computer Science Curriculum, Part 1. *Computing in Science and Engineering*, 19(5):58–67.

Allen, M. P. and Tildesley, D. J. (2017). *Computer Simulation of Liquids: Second Edition*. Oxford University Press, Oxford.

Bell, R. L. and Trundle, K. C. (2008). The use of a computer simulation to promote scientific conceptions of moon phases. *Journal of Research in Science Teaching*, 45(3):346–372.

Bezemer, J. and Kress, G. (2008). Writing in Multimodal Texts. *Written Communication*, 25(2):166–195.

Bocconi, S., Chioccariello, A., and Earp, J. (2018). The Nordic Approach To Introducing Computational Thinking And Programming In Compulsary Education. *Report prepared for the Nordic@BETT2018 Steering Group*.

Bruner, J. S. (1977). *The Process of Education*. Harvard paperback. Harvard University Press, Cambridge, MA.

Caballero, M. D. (2015). Computation across the curriculum: What skills are needed? *2015 Physics Education Research Conference Proceedings*, pages 79–82.

Caballero, M. D., Burk, J. B., Aiken, J. M., Thoms, B. D., Douglas, S. S., Scanlon, E. M., and Schatz, M. F. (2014). Integrating Numerical Computation into the Modeling Instruction Curriculum. *The Physics Teacher*, 52(1):38–42.

Caballero, M. D., Greco, E. F., Murray, E. R., Bujak, K. R., Jackson Marr, M., Catrambone, R., Kohlmyer, M. A., and Schatz, M. F. (2012a). Comparing large lecture mechanics curricula using the force concept inventory: A five thousand student study. *American Journal of Physics*, 80(7):638–644.

Caballero, M. D., Kohlmyer, M. A., and Schatz, M. F. (2012b). Fostering Computational Thinking in Introductory Mechanics. *AIP Conference Proceedings*.

Caballero, M. D. and Pollock, S. J. (2014). A model for incorporating computation without changing the course: An example from middle-division classical mechanics. *American Journal of Physics*, 82(3):231–237.

Chabay, R. and Sherwood, B. (2008). Computational physics in the introductory calculus-based course. *American Journal of Physics*, 76(4):307–313.

Chabay, R. W. and Sherwood, B. A. (1999). Bringing atoms into first-year physics. *American Journal of Physics*, 67(12):1045–1050.

Chabay, R. W. and Sherwood, B. A. (2004). Modern mechanics. *American Journal of Physics*, 72(4):439–445.

Chang, K.-E., Chen, Y.-L., Lin, H.-Y., and Sung, Y.-T. (2008). Effects of learning support in simulation-based physics learning. *Computers & Education*, 51(4):1486 – 1498.

diSessa, A. (2001). *Changing Minds: Computers, Learning, and Literacy*. Bradford Books. MIT Press, Cambridge, MA.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction*, 10(3):105–225.

Dwyer, H. A., Boe, B., Hill, C., Franklin, D., and Harlow, D. (2014). Computational Thinking for Physics: Programming Models of Physics Phenomenon in Elementary School. *2013 Physics Education Research Conference Proceedings*, pages 133–136.

Elmgren, M. and Henriksson, A.-S. (2015). *Academic Teaching*. Studentlitteratur AB, Lund.

Eriksson, U., Linder, C., Airey, J., and Redfors, A. (2014). Introducing the anatomy of disciplinary discernment: an example from astronomy. *European Journal of Science and Mathematics Education*, 2(3):167–182.

European Commission (2018). Reform of EU Data Protection Rules. `https://gdpr-info.eu/` Accessed 2019-11-26.

Fredlund, T. (2015). *Using a Social Semiotic Perspective to Inform the Teaching and Learning of Physics*. Uppsala: Acta Universitatis Upsaliensis.

Fredlund, T., Linder, C., Airey, J., and Linder, A. (2014). Unpacking physics representations: Towards an appreciation of disciplinary affordance. *Phys. Rev. ST Phys. Educ. Res.*, 10:020129.

Fry, B., Reas, C., and Shiffman, D. (accessed April 3, 2019). *The Processing Foundation*. `https://processingfoundation.org/`.

Gerestrand, A. (2017). *Programmering som ett verktyg för lärande*. Gothenburg University, Gothenburg. Master's Thesis.

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. Houghton, Mifflin and Company, Boston, MA.

Glaser, B. and Strauss, A. (1967). *The Discovery of Grounded Theory: Strategies for Qualitative Research*. Observations (Chicago, Ill.). Aldine.

GoPro Inc (2019). GoPro Hero 6. `https://gopro.com/en/us/shop/cameras`.

Guba, E. G. and Lincoln, Y. S. (1982). Epistemological and methodological bases of naturalistic inquiry. *Educational Communication & Technology*, 30(4):233–252.

Halliday, M. A. K. (2009). Language as social semiotic: towards a general sociolinguistic theory. *Language and Society*, 10(1975):169–201.

Hestenes, D. (1987). Toward a modeling theory of physics instruction. *American Journal of Physics*, 55(5):440–454.

Hewish, A., Bell, S. J., Pilkington, J. D. H., Frederick Scott, P., and Collins, R. A. (2014). 74. Observation of a Rapidly Pulsating Radio Source. *A Source Book in Astronomy and Astrophysics, 1900–1975*, 217:709–713.

Ingerman, Å., Linder, C., and Marshall, D. (2009). The learners' experience of variation: following students' threads of learning physics in computer simulation sessions. *Instructional Science*, 37(3):273–292.

Institute of Physics and Hardman, M. (2019). Misconceptions and Naïve Ideas in Physics. `https://spark.iop.org/misconceptions`.

Jewitt, C., Kress, G., Ogborn, J., and Tsatsarelis, C. (2001). Exploring learning through visual, actional and linguistic communication: The multimodal environment of a science classroom. *Educational Review*, 53(1):5–18.

King, A. (1993). From Sage on the Stage to Guide on the Side. *College Teaching*, 41(1):30–35.

Kolb, D. A. (1984). *Experiential Learning: Experience as the Source of Learning and Development*. Prentice Hall, Inc., Upper Saddle River, NJ.

Kress, G., Jewitt, C., Ogborn, J., and Charalampos, T. (2014). *Multimodal Teaching and Learning: The Rhetorics of the Science Classroom*. Bloomsbury Classics in Linguistics. Bloomsbury Publishing, London.

Kress, G. and van Leeuwen, T. (2006). *Reading images: the grammar of visual design*. Routledge, London.

Kullberg, A. (2012). Students' open dimensions of variation. *International Journal for Lesson and Learning Studies*, 1(2):168–181.

Kullberg, A., Runesson Kempe, U., and Marton, F. (2017). What is made possible to learn when using the variation theory of learning in teaching mathematics? *ZDM*, 49(4):559–569.

Linder, C. (2013). Disciplinary discourse, representation, and appresentation in the teaching and learning of science. *European Journal of Science and Mathematics Education*, 1(2):43–49.

Linder, C. and Priemer, B. (2013). A social semiotic understanding of representation linking and affordance in physics: The refraction of light. *The 10th European Science Education Research Association Conference, University of Cyprus, Nicosia, 2-7th September*.

Lo, M. (2012a). *Variation Theory and the Improvement of Teaching and Learning*. Gothenburg studies in educational sciences. Acta universitatis Gothoburgensis.

Lo, M. L. (2012b). Towards a science of the art of teaching: Using variation theory as a guiding principle of pedagogical design. *International Journal for Lesson and Learning Studies*, 1(1):7–22.

Lyman, F. (1987). "Think-Pair-Share": An Ending Technique. *MAA-CIE Cooperative News*, 1.

Marton, F. (2015). *Necessary Conditions of Learning*. Taylor & Francis.

Marton, F. and Booth, S. (1997). *Learning and Awareness*. Educational psychology series. L. Erlbaum Associates.

Mavers, D. and Will, G. (2020). What is a mode? `https://multimodalityglossary.wordpress.com/mode-2/` Accessed: 2020-01-22.

McCloskey, M. and Kohl, D. (1983). Naive physics: The curvilinear impetus principle and its role in interactions with moving objects. *Journal of Experimental Psychology: Learning Memory and Cognition*, 9(1):146–156.

McDermott, L. C. (1974). Practice-teaching program in physics for future elementary school teachers. *American Journal of Physics*, 42(9):737–742.

McDermott, L. C. and Redish, E. F. (1999). Resource letter: PER-1: Physics education research. *American Journal of Physics*, 67(9):755–767.

Okebukola, P. A. and Ogunniyi, M. B. (1984). Cooperative, competitive, and individualistic science laboratory interaction patterns—effects on students' achievement and acquisition of practical skills. *Journal of Research in Science Teaching*, 21(9):875–884.

Papert, S. (1980). *Mindstorms: Children, computers and powerful ideas*, volume 1. Basic Books Inc., New York, NY.

Perkins, K., Adams, W., Dubson, M., Finkelstein, N., Reid, S., Wieman, C., and LeMaster, R. (2006). Phet: Interactive simulations for teaching and learning physics. *The Physics Teacher*, 44(1):18–23.

Prain, V. and Tytler, R. (2013). Representing and learning in science. In *Constructing Representations to Learn in Science*, pages 1–14.

Redish, E. F. (2003). Teaching Physics with the Physics Suite. page 216.

Redish, E. F. (2014). Oersted Lecture 2013: How should we think about how our students think? *American Journal of Physics*, 82(6):537–551.

Redish, E. F. and Wilson, J. M. (1993). Student programming in the introductory physics course: MUPPET. *American Journal of Physics*, 61(3):222–232.

Sand, O. P., Odden, T. O. B., Lindstrøm, C., and Caballero, M. D. (2018). How computation can facilitate sensemaking about physics: A case study. *2018 Physics Education Research Conference Proceedings*, pages 1–4.

Skolverket (2016). Redovisning av uppdraget om att föreslå nationella it- strategier för skolväsendet – förändringar i läroplaner, kursplaner, ämnesplaner och examensmål English: Swedish National Agency for Education: Presentation of the assignment to propose national IT strategies for the school system - changes in curricula, syllabuses, subject plans and degree objectives.

Stein, P. (2007). *Multimodal pedagogies in diverse classrooms: Representation, rights and resources*. Routledge, London.

Svensson, K. (2020). 2D Physics Simulations using Processing IDE for Physics Education Research - Workshop 2018. `10.5281/zenodo.3607528`.

Thuné, M. and Eckerdal, A. (2009). Variation theory applied to students' conceptions of computer programming. *European Journal of Engineering Education*, 34(4):339–347.

Trundle, K. C. and Bell, R. L. (2010). The use of a computer simulation to promote conceptual change: A quasi-experimental study. *Computers and Education*, 54(4):1078–1088.

Tytler, R. and Prain, V. (2010). A framework for re–thinking learning in science from recent cognitive science perspectives. *International Journal of Science Education*, 32(15):2055–2078.

Uzezi, J. G. and Zainab, S. (2017). Effectiveness of guided-inquiry laboratory experiments on senior secondary schools students academic achievement in volumetric analysis. *American Journal of Educational Research*, 5(7):717–724.

van Rossum, G. (1995). Python tutorial. Technical Report CS-R9526, Centrum voor Wiskunde en Informatica (CWI), Amsterdam.

Volkwyn, T. S., Airey, J., Gregorcic, B., and Heijkenskjöld, F. (2019). Transduction and Science Learning: Multimodality in the Physics Laboratory. *Designs for Learning*, 11(1):16–29.

Watson, R., Prieto, T., and Dillon, J. S. (1995). The effect of practical work on students' understanding of combustion. *Journal of Research in Science Teaching*, 32(5):487–502.

Wilensky, U. (1999). Netlogo. *Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.*

Wilson, J. M. and Redish, E. F. (1986). Using Computers. *Computer*, 34:551–562.

Wood, D. F. (2003). Problem based learning. *BMJ*, 326(7384):328–330.

Zhou, D., Burges, C. J. C., and Tao, T. (2007). Transductive link spam detection. In *AIRWeb*.

Scientific publications

11 Author contributions

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

I constructed a workshop for upper secondary education pupils, that introduces physics simulations in the Processing IDE using the Python Programming Language. During the workshop, I lectured, filmed and performed the interviews the students. The co-authors UE and AMP advised in the construction of the workshop and data collection process, they were also part of the analysis process and the commented on the text of the paper.

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

I did a literature study on programming in physics education and put it to the context of the theoretical framework of Social Semiotics and Variation Theory, I also related the results in Paper I to the theoretical framework explored in this paper. UE and AMP helped with the literature study and putting every piece of the theory together in a programming context. They were also advisers while I wrote and composed the paper.

11.3 Paper III: Students making sense of motion in a vertical roller coaster loop

I was the technical assistant during the data collection session and I took part in the interview as a supporting role. I took on the role of Data Steward for the project and wrote the consent forms and handled the data storage. I was also part of the analysis of the data and contributed to the paper through smaller texts, editing and figures.

11.4 Paper IV: The concept of a Transductive Link

A shorter paper outlining the definition and idea behind the concept of a Transductive Link in social semiotics. The term was used in paper I and by Airey and Linder (2017), but it was not explored nor defined. The paper is a theoretical contribution to the social semiotics framework. UE gave insightful comments during the short write-up of this paper.