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On the analytical engagement of social semiotics and variation theory in physics education research

MOA ERIKSSON
FACULTY OF SCIENCE | LUND UNIVERSITY

On the analytical engagement of social semiotics and variation theory in physics education research

Students' learning challenges in undergraduate physics has been getting more and more attention in Sweden in the recent years. To contribute to the body of knowledge and understanding of these challenges, this licentiate thesis seeks to investigate the analytical combination of two theoretical frameworks used in physics education research; social semiotics and variation theory of learning. This thesis presents research that investigates this combination analytically and suggests a model for a way in which this combination can be fruitfully applied.

Moa Eriksson has an undergraduate degree in mathematics and physics and also holds a teacher certificate for teaching in physics and mathematics at upper secondary school in Sweden. Ever since before starting her teacher studies she has had an interest in learning and how to help others learn. She hopes that her research will be able to inform physics teacher educations in Sweden and to help teachers better meet their students and help them overcome any challenges in learning physics that they might have.

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On the analytical engagement of social semiotics and variation theory in physics education research

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Moa Eriksson

LUND UNIVERSITY

LICENTIATE DISSERTATION

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Abstract
In this licentiate thesis, I explore how two theoretical frameworks—social semiotics and the variation theory of learning—used in physics education research, can be fruitfully combined to obtain additional analytical tools for analysing student learning in introductory level university physics. Each theoretical framework has on their own, or together with other frameworks, been successfully applied for analysing both individual and collective learning, but the combination of the two has yet not been fully explored. Social semiotics is concerned with the communication, using different semiotic resources (such as spoken and written language, mathematics, diagrams, gestures, and apparatus), between people within a certain discourse. Variation theory suggests that learning can only be successful if a person is able to discern the critical aspects of a phenomenon. This discernment is seen to be dependent on being exposed to purposeful variation within this aspect.

In order to study this analytical combination, I made use of two case studies; I studied (1) physics students' understanding of plus (+) and minus (–) signs in a one-dimensional kinematics contexts; and, (2) students' collective communication and learning progression in group work activities solving problems in circular motion. In both cases I explored how the concept of 'relevance structure' could be used analytically to understanding students' learning challenges in physics. For the first case study I was able to identify four qualitative different categories of students' individual relevance structure for of how students 'read' and 'use' these algebraic signs in this context. Through the analysis connected to the data set used for the second case study I was also able to identify two different approaches to viewing a circular motion problem—a static and dynamic approach—suggested to be the result of students' 'enacted relevance structure', and also empirically show how social semiotics and variation theory could be analytically combined in a powerful way in qualitative analysis.

Conclusions that I can draw from the research presented in this thesis is that students' relevance structure—what they perceive as being relevant—seem to have a high influence on students' ability to discern disciplinary relevant aspects (DRAs) of the phenomenon which they are studying. I suggest that the relevance structure may act as a 'filter' for students to be able to make the appropriate disciplinary discernment even though they experience purposeful variation within a dimension of variation.

From the research presented in this licentiate thesis, I have been able to identify and suggest both theoretical and methodological contributions to physics education research and I end this thesis with suggesting implications for teaching and learning, as well as making suggestions for future research.

Key words
social semiotics; variation theory; relevance structure; dimensions of variation; semiotic resources

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Moa Eriksson

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“It is better to know how to learn than to know”
– Dr. Seuss

List of papers and supporting work

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

I. **Eriksson, M**., Linder, C., & Eriksson, U. (2019). Towards understanding learning challenges involving sign convention in introductory level kinematics. In 2018 *Physics Education Research Conference Proceedings*. Washington, DC.

II. **Eriksson, M.**, Eriksson, U, Linder, C. (2020) *Using social semiotics and variation theory to analyse learning challenges in physics: a methodological case study*. Manuscript submitted for publication.

This thesis also draws on the following supporting papers and conference presentations.

Supporting papers

Pendrill, A.-M., **Eriksson, M**., Eriksson, U., Svensson, K., & Ouattara, L. (2019). Students making sense of motion in a vertical roller coaster loop. *Physics Education*, *54*, 065017.

Other supporting work

Eriksson, M., Eriksson, U., Linder, C., Pendrill, A.-M., & Ouattara, L. (2019). Students' understanding of perceived types of forces within circular motion. Presented at the American Association of Physics Teachers (AAPT) Summer Meeting, Provo, UT, USA, 20-24 July 2019.

Eriksson, M., Eriksson, U., Linder, C., Pendrill, A.-M., & Ouattara, L. (2019) Circular motion revisited – static solution to a dynamic problem? Poster presented at the

American Association of Physics Teachers (AAPT) Summer Meeting, Provo, UT, USA, 20-24 July 2019.

Eriksson, M., Eriksson, U., Linder, C., Pendrill, A.-M., & Ouattara, L. (2019). New insights into the challenges of learning circular motion - a variation theory and social semiotics case study. Presented at GIREP conference, Budapest, Hungary 1-5 July 2019.

Eriksson, M., Eriksson, U., & Linder, C. (2018). Multimodal situated configurations in a physics interactive learning environment dealing with circular motion. Presented at the 9th International Conference on Multimodality (9ICOM), Odense, Denmark, 15-17 August 2018.

Eriksson, M., Linder, C., & Eriksson, U. (2018). Towards understanding learning challenges involving sign convention in introductory level kinematics. Poster presented at the Physics Education Research Conference (PERC), Washington D.C., USA, 1-2 August 2018.

Eriksson, M. (2018). Algebraic signs in introductory kinematics: a redundant educational issue? Poster presented at the American Association of Physics Teachers (AAPT) Summer Meeting, Washington D.C., USA, 28 July - 1 August 2018.

Eriksson, M., Linder, C., & Eriksson, U. (2018). Students' understanding of algebraic signs: An underestimated learning challenge? Presented at the American Association of Physics Teachers (AAPT) Summer Meeting, Washington D.C., USA, 28 July - 1 August 2018.

Eriksson, M., Eriksson, U., & Linder, C. (2018). Studenters användning av semiotiska resurser: Hur studenter skapar mening kring cirkelrörelse. Presented at Från forskning till fysikundervisning, Lund, Sweden, 10–11 April 2018.

Table of Contents

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"my" many children for providing me with so much joy and laughter during this period. I have not had been able to do this without you! I love you!

Abstract

In this licentiate thesis, I explore how two theoretical frameworks—social semiotics and the variation theory of learning—used in physics education research, can be fruitfully combined to obtain additional analytical tools for analysing student learning in introductory level university physics. Each theoretical framework has on their own, or together with other frameworks, been successfully applied for analysing both individual and collective learning, but the combination of the two has yet not been fully explored. Social semiotics is concerned with the communication, using different semiotic resources (such as spoken and written language, mathematics, diagrams, gestures, and apparatus), between people within a certain discourse. Variation theory suggests that learning can only be successful if a person is able to discern the critical aspects of a phenomenon. This discernment is seen to be dependent on being exposed to purposeful variation within this aspect.

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Conclusions that I can draw from the research presented in this thesis is that students' relevance structure—what they perceive as being relevant—seem to have a high influence on students' ability to discern disciplinary relevant aspects (DRAs) of the phenomenon which they are studying. I suggest that the relevance structure may act as a 'filter' for students to be able to make the appropriate disciplinary discernment even though they experience purposeful variation within a dimension of variation.

From the research presented in this licentiate thesis, I have been able to identify and suggest both theoretical and methodological contributions to physics education research and I end this thesis with suggesting implications for teaching and learning, as well as making suggestions for future research.

Svensk sammanfattning

Lärande i fysik, precis som i andra discipliner, handlar om att bli en del av fysikdiskursen genom att lära sig den disciplinära kommunikationen som används. Att bli en del av diskursen handlar därför i mångt och mycket om att lära sig ett nytt språk. Denna disciplinära kommunikation—språket—framförs med hjälp av olika *semiotiska resurser* (exempelvis talat eller skrivet språk, matematik, gester, diagram eller aktiviteter) och det krävs att studenter lär sig att använda dessa resurser på ett, för disciplinen, korrekt sätt. Den forskning som presenteras i den här licentiatavhandlingen fokuserar på just denna disciplinära kommunikation.

Syftet med min forskning har varit att, från ett analytiskt perspektiv, studera den disciplinära kommunikationen i fysik med utgångspunkt i två teoretiska ramverk; *socialsemiotik* och *variationsteori*. Dessa ramverk har var för sig i olika forskningsstudier applicerats på ett framgångsrikt sätt för att kunna öka förståelsen för studenters lärandeutmaningar i fysik. Däremot har kombinationen av dessa ramverk inte studerats i någon vidare omfattning. Denna licentiatavhandling syftar därför till att studera hur dessa ramverk kan kombineras ur ett analytiskt perspektiv för att få ytterligare förståelse för studenters lärandeutmaningar i fysik. Mer specifikt har jag i min forskning avsett att studera både hur studenter förstår specifika semiotiska resurser, och hur de själva använder olika typer av resurser för att bidra till lärandet i fysik, både individuellt och kollektivt i en grupp.

För att studera denna kombination har jag genomfört två fallstudier inom två olika kontexter i fysik på introduktionsnivå på universitetet. Den första fallstudien utfördes med studenter på tekniskt basår i Sverige samt med lärarstudenter i Sydafrika. Frågeställningen för fallstudien var att identifiera kategorier av relevansstruktur som beskriver på vilka kvalitativt skilda sätt som dessa studenter upplever användningen av de algebraiska tecknen plus (+) och minus (–) inom endimensionell vektorkinematik. Genom denna fallstudie lyckades jag identifiera fyra kategorier av *relevansstruktur* som beskriver hur studenter 'läser av' (eng. *read*) och 'använder' (eng. *use*) dessa algebraiska tecken. Dessa kategorier är hierarkiskt ordnade från det minst avancerade sättet att förstå dessa tecken till det mest avancerade sättet. Data till denna fallstudie bestod av skriftliga enkätsvar samt ljudinspelningar från uppföljningsintervjuer med utvalda studenter. Totalt deltog 84 studenter (60 svenska och 24 sydafrikanska) i studien genom att svara på enkäten. Resultat från fallstudien visade bland annat att studenterna hade svårigheter att koppla dessa algebraiska tecken till koordinatsystem, det vill säga, de uppvisade svårigheter att förstå vad dessa teckens inneboende mening egentligen var.

Den andra fallstudien som den här avhandlingen bygger på genomfördes med kandidatstudenter i fysik på ett svenskt universitet. Studenterna studerades då de gruppvis löste problem kring cirkelrörelse. Den data som användes i studien bestod av videofilmer av två olika grupper (fyra studenter i varje grupp) av studenter som arbetade med antingen ett cirkelrörelseproblem i vertikal led eller i horisontell led. Som ett led i analysen gjorde jag 'multimodala transkriptioner' som visade både studenternas tal och övriga semiotiska system som användes—i synnerhet gester, skisser, diagram och matematik. I min analys använde jag mig av koncept från både socialsemiotik och variationsteori för att skapa mig en förståelse av studenternas lärandeprogression. Genom att studera studenternas diskussioner utifrån dessa multimodala transkriptioner, med fokus på deras sätt att kommunicera, kunde jag först identifiera vilka disciplinärt relevanta aspekter studenterna fokuserar på samt vilka semiotiska resurser de använder i deras kommunikation. Därefter kunde jag identifiera studenternas 'uttryckta' (eng. *enacted*) relevansstruktur och identifiera två olika sätt att se på ett cirkelrörelseproblem. Slutligen kunde jag identifiera strukturen på studenternas diskussioner och se att de spontant genererade variation kring dessa disciplinärt relevanta aspekter med hjälp av olika semiotiska resurser. Detta ledde mig till att, utifrån denna fallstudie, föreslå en analytisk modell för hur socialsemiotik och variationsteori gemensamt kan tillämpas för att förstå studenters lärandeutmaningar i fysik; (1) med hjälp av socialsemiotik identifiera de disciplinärt relevanta aspekter som studenterna tar upp i sina diskussioner, samt vilka semiotiska resurser som används; (2) identifiera studenternas 'uttryckta' relevansstruktur; och, (3) identifiera, med hjälp av variationsteori, på vilka sätt studenterna kommunicerar med fokus på deras genererade variation.

Genom mina två fallstudier har jag kunnat se att studenter ofta inte lyckas urskilja de disciplinärt relevanta aspekter som utvalda semiotiska resurser används för att kommunicera. Mina slutsatser från resultaten är därför att konceptet relevansstruktur är ett kraftfullt analytiskt verktyg för att ytterligare kunna förstå vilka utmaningar studenterna ställs inför under deras lärande i fysik. Studenters uttryckta relevansstruktur kan ses som ett filter som påverkar vad studenterna har för möjligheter att urskilja kritiska aspekter för ett visst fenomen som studeras. Därför föreslår jag att det är det ytterst kritiskt att lärare blir medvetna om att vad studenterna ser som relevant för ett visst problem—deras relevansstruktur—i allra högsta grad påverkar studenternas förmåga att göra en disciplinär urskiljning av kritiska aspekter i fysik.

Abbreviations

AJP	*American Journal of Physics*
DBER	*Discipline-Based Education Research*
DoV	*Dimension of Variation*
DRA	*Disciplinary Relevant Aspect*
EJP	*European Journal of Physics*
GDPR	*General Data Protection Regulation*
GIREP	*Groupe International de Recherche sur l'Enseignement de la Physique*
ICPE	*International Commission for Physics Education*
IE	*Interactive Engagement*
N1	*Newton's first law of motion*
N3	*Newton's third law of motion*
NRCF	*Nationellt resurscentrum för fysik [National Resource Center for Physics Education]*
PER	*Physics Education Research*
PERC	*Physics Education Research Conference*
PRPER	*Physical Review Physics Education Research*

Notes for the reader

About the use of language

Throughout this thesis I have chosen to use the gender-neutral pronoun they/their/theirs when appropriate, instead of he/him/his or she/her/hers when I refer to a generic individual student.

Furthermore, I am using the first-person singular pronoun I/me/my when, for example, referring to the choices I have made when writing and structuring this thesis. Using this style of language is a deliberate choice in order to make the thesis kappa being able to stand on its own and to improve the flow between sections. However, it is important to note that it is not in any way my intention to portray the research presented in this thesis as solely my own, as it is been the result through a close, collaborative effort between myself and my supervisors. The extended discussion of the research questions and implications from these results, however, are the result of my own ideas.

About reused material

This licentiate thesis is structured in such way that it can be read from start to finish without having to also read the two papers which are included at the end. Because of this, some sections of this thesis are inevitably identical or almost identical to the corresponding sections in the papers. I will, by making this note, address this issue and also clarify, as mentioned above, that I, in no way, are trying to portray the research reported in the papers as solely my own. Both papers have instead been crafted through a collaborative effort between me and my co-authors.

1 Introduction

When asked about the topic of my PhD, people often have one of two comments to my answer; “You must be really smart!” or “That must be really difficult!”. Similarly, when asked about my undergraduate degree (I am a licenced mathematics and physics teacher for upper secondary school in Sweden—sv. ‘*gymnasiet*’) I often receive similar comments; “Wow, you must be so smart” or, “I didn’t like physics at all when I was in school”. My own reply to these comments varies, but the thoughts that enter my mind is most often focused on what their own physics education looked like when they were in school. Being a teacher myself, I know the kind of impact that teachers have on their students, but also the challenges that teachers encounter when, to the best of their ability, trying to help their students learn the subject. It was with thoughts like these that I turned my interest towards physics education research (PER).

A view shared among many practitioners within PER is that learning physics is a lot like learning a language. A language with its own ‘words’, grammar and other rules. This means that educators[1] expect their students to learn the language of physics. However, this “learning the language” is often not explicitly brought forward in teaching. At the same time, students are expected to learn to discern the disciplinary way of knowing—metaphorically known as “reading the sky” (U. Eriksson, 2019).

Within PER there has over the past 15 years been a development of the way to understand the disciplinary communication used in university physics teaching and learning (see Airey & Linder, 2009, 2017). This perspective of studying the communicative practices used within a discipline—known as *social semiotics* (e.g. Hodge & Kress, 1988; van Leeuwen, 2005)—can be powerfully used to gain insights into the ways both teachers and students communicate in a disciplinary way. I believe that teachers can benefit a great deal with such knowledge to be able to not only know what disciplinary representations provide what knowledge, but also to be able to consider the disciplinary ways that knowledge is conveyed in—to help their students to ‘read the sky’. A powerful way of dealing with such communication will provide tools for students to be fully able to internalize the physics knowledge and to make it their own.

[1] I will be using ’teachers’, ‘educators’ and ‘instructors’ interchangeably throughout this thesis.

A particular piece to the puzzle of building this social semiotics framework for physics teaching and learning is how one can apply social semiotics to theoretically understand powerful ways of teaching. This part of the puzzle was studied by Fredlund, Airey, and Linder (2015) who drew on this social semiotic framework and suggested a theoretical model, that could be used for teachers, to maximize the learning in university physics education. The theoretical model proposed by Fredlund et al. comprised three parts:

1. identify the disciplinary relevant aspects (DRAs) for the particular task;
2. select the appropriate semiotic resources that will give access to these DRAs; and,
3. create variation within the selected semiotic resources.

The third step in this model proposed that teachers should create purposeful variation within a chosen semiotic resource to help students discern the critical aspect. This variation is based on the ideas within the *variation theory of learning* (Marton, 2015; Marton & Tsui, 2004). To summarize, the study by Fredlund et al., that I have presented here, proposes a theoretically based three-step model for how teachers can enhance the possibilities for learning in university level physics. Variation theory has over the past 40 years developed to become a frequently used theoretical framework for studying and understanding learning.

Similar as with the study by Fredlund et al, most studies making use of variation theory has studied variation as created by teachers (for example, Fraser & Linder, 2009 and Linder & Fraser, 2009). However, in contrast to Fredlund's study, Ingerman, Linder, and Marshall (2009) studied how students themselves create variation and based their analysis on empirical data of students working in groups. Their analytic grounding was variation theory, which provided them with tools to analyse students' discussion, looking especially at how students created variation within and across critical aspects for a particular phenomenon.

1.1 Overarching aims

Drawing on the results of the studies presented above, my particular focus for this thesis is to study students' learning in university level physics from a theoretical perspective but drawing on empirical data. Thus, my overarching aim for this thesis is to study the ways in which social semiotics and variation theory of learning fruitfully could be combined in an analytical way to increase understanding of students' learning challenges in physics, as has previously been suggested by Linder (2012). Specifically, I want to study how students read and use disciplinary *semiotic resources*—representations, tools and activities (Airey & Linder, 2009)—in physics learning and how students' individually created variation, using either disciplinary or non-disciplinary resources, can be understood in terms of these theoretical frameworks. Further, I want to study how this student-created variation could be contrasted to Fredlund et al.'s (2015) theoretical proposal for teacher-created variation. Although my research is directed towards theoretical and methodological contributions, it has been my aim from the beginning to provide knowledge for educators that will improve the possibilities for learning undergraduate level physics.

1.2 Research questions

Based on the research aims presented above, this licentiate thesis is structured around the following research questions (RQs):

RQ1 *What are the individual level categories of variation of experiencing relevance structure with regard to algebraic signs (+ and –) in introductory kinematics problem solving in university physics education?*

RQ2 *In the context of students' learning in tutorial type group work:*

- *a) in what different ways could students' reasoning be characterized when trying to find the forces acting on an object in circular motion?*
- *b) how can the theoretical framework of social semiotic be fruitfully combined with variation theory of learning in an analytical way to contribute to the theoretical understanding of students' learning in group works?*

1.3 Knowledge claims of this thesis

The work presented in this thesis has produced knowledge claims across these broad topics of physics teaching and learning.

- Social semiotics: This thesis provides an exploration of how social semiotics can be complemented with the variation theory of learning in gaining new methodological insights towards analysing students' group work in physics.
- The variation theory of learning: This thesis provides understanding of how students' relevance structure can give insights into how semiotic resources are 'read' and 'used', and how students' individual relevance structure plays a role in the development of collective learning in group works.

- Physics education research: This thesis provides an in-depth exploration of how two powerful theoretical frameworks can be fruitfully applied as a combined analytic tool for understanding learning challenges in physics. This combination has not been studied at this level before.
- Physics teaching and learning: This thesis provides knowledge for teachers that focuses on what students find relevant for a certain situation affects their probability for solving the particular problem.

1.4 Structure of this thesis

This licentiate thesis is built around seven chapters in which I have tried to give a full transparent view of the research that makes up this thesis. In Chapter 2 I start by situating my research in the existing body of physics education research (PER) by giving the reader a literature review of the field. In this chapter I will also discuss PER in an international and national perspective. In Chapter 3 I provide a literature review of the two theoretical frameworks that I have applied in my research. The first being *social semiotics*, and the second being *variation theory of learning*. In Chapter 4 I give the reader a detailed description of the methodology used for the two papers that make up this thesis. This chapter include a description of the method of data collection and analysis used as well as a discussion about the trustworthiness and ethics concerned with this research. Chapter 5 includes details about the analysis process for each of the two data sets. Chapter 6 gives a summary of the results obtained from the research, and also answers the research questions set up in Chapter 1. The last chapter of this thesis, Chapter 7, includes a discussion about the findings, as well as some thoughts for the future.

2 Literature review

In this chapter I will give an introduction to the field in which my work is situated namely Physics Education Research (PER). I will provide an overview of the PER field, as well as some important contributions to the field, and discuss where my work is situated in the collective knowledge in the field. At the end of the chapter I will discuss more explicit where I position myself within PER.

For me, the relevant PER is mostly focused on teaching and learning at university level and can be seen as a specialized form of discipline-based education research (DBER). DBER is defined as an area that "investigates learning and teaching in a discipline from a perspective that reflects the discipline's priorities, worldview, knowledge, and practices" (National Research Council, 2012, p. 1). Since my own research is focused on teaching and learning of physics at the university level, I will in this review mostly cover research at this level. However, there is a wide variety of education research being done at school level, both in science in general and physics in particular.

2.1 Physics education research

Physics education research is a research field which focuses on the teaching and learning of physics. This includes, for example, the understanding of learning challenges that students encounter when learning physics. While a majority of the PER work that has been conducted and published around the world historically comes from PER groups situated in the United States, it should be noted that the field of PER covers all parts of the world and is not in any way exclusive to the US. Many groups around the world are doing PER while not publishing primarily in English. In an international perspective, evidence of the wider field can be found in proceedings of conferences organised by organisations such as *Groupe International de Recherche sur l'Enseignement de la Physique*[2] (GIREP) and *International Commission for Physics Education*[3] (ICPE).

[2] https://girep.org

[3] http://iupap.org/commissions/physics-education/

Some of the most known PER groups are situated at the Universities of Washington, Maryland, and Colorado. On the PER-Central homepage[4] there are at the time of writing this thesis (April 2020) only 15 active PER groups listed outside of the US. Among the listed international PER groups are the groups in Uppsala, Sweden, that contributes with theoretical and methodological development, and Cape Town, South Africa, that contributes with insights into, for example, physics laboratory teaching and learning. However, in as recent as 2017, Lund University took steps towards having a pure PER group of their own. This group is focused on theoretical and methodological contributions to frameworks used in PER and Astronomy Education Research (AER).

In recent years, PER has grown into a large research field and is mainly focused on the teaching and learning of university-level physics and how to improve student learning. The initial emphasis of PER was historically on students' conceptual understanding of introductory mechanics (Clement, 1982; McCloskey, 1983; McDermott, 1984; Peters, 1982), but recent contributions to the field reveal that research is now conducted in almost all parts of university physics curriculum. Examples of this can be found from the many papers presented at PER conferences, e.g. *Physics Education Research Conference*[5] (PERC), and in peer-reviewed journals such as *American Journal of Physics*[6] (AJP), *European Journal of Physics*[7] (EJP), and *Physical Review Physics Education Research*[8] (PRPER).

2.2 Main topical areas of PER

Research in PER is typically clustered around a few topical areas. Some recent overviews of a number of topical areas have been published to help give an overview of PER and help young researchers in PER to navigate the field (e.g. Beichner, 2009; Cummings, 2011; Docktor & Mestre, 2014). I have, from the available overviews, formed my own view of the topical areas of PER which I aim to describe in the following sub-sections[9]. I have divided my overview in this licentiate thesis into six topical areas of PER research;

[4] The PER-Central homepage (https://www.per-central.org) is a collection of resources for physics education researchers.

[5] https://www.per-central.org/perc/

[6] http://aapt.scitation.org/journal/ajp

[7] http://iopscience.iop.org/journal/0143-0807

[8] https://journals.aps.org/prper/

[9] Note that these sub-sections are not exhaustive, and work mentioned in one area might also be relevant in another. However, the categorization in this chapter is my view of the field.

Conceptual understanding and conceptual change, Instructional material, Assessment instruments, Cognitive psychology, Attitudes and beliefs, and Representations in PER.

2.2.1 Conceptual understanding and conceptual change

Initial work in PER was almost exclusively focused on students' conceptual understanding. In the US, Arnold Arons was an early advocator for changing physics education, and his work was the starting point of successful research in physics education (Arons, 1998). Arons, together with Robert Karplus, also made large contributions to the development of the new physics curriculum, with an interest in a more inquiry-based curriculum (Meltzer & Otero, 2015, p. 452). A student of Arons, Lillian McDermott, expanded in the late 1970s and 1980s on his work by, for example, developing a teacher preparation curriculum and making physics more accessible for all students (e.g. McDermott, 1974; Rosenquist & McDermott, 1987). She, together with her student David Trowbridge, also studied students' conceptual difficulties understanding velocity and acceleration in one dimensional kinematics (Trowbridge & McDermott, 1980, 1981). Other early work on students' conceptual understanding include Brown and Clement (1989) who investigated how students' 'misconceptions'[10] (see also Section 2.2.4) could be probed through the use of analogies in teaching.

In Africa, Hugh Helm, in the early 1980s, studied students' misconceptions in introductory physics at different universities around South Africa (Helm, 1980). To obtain information about the extent of these conceptions, Helm constructed a "misconceptions test" which was distributed to university students, teachers, and high-school students for comparison. In Europe, Laurence Viennot was an early and persistent promoter of research in physics education. She, for example, studied students' reasoning in physics at different educational levels (Viennot, 1979).

Related to students' conceptual understanding is the process of conceptual change in physics. Two early examples are Tiberghien (1994) who found two main types of conceptual change among students when talking about heat, and Hewson (1982) who studied conceptual change in the context of learning about special relativity. Following the results of the research mentioned above and other examples, many assessment tools have been constructed with the aim of testing conceptual understanding (see Section 2.2.3).

[10] The term "misconceptions" is somewhat misleading and is subject to discussion between researchers. Other commonly used terms include 'preconceptions', 'naïve conceptions' and 'alternative conceptions' (see Section 2.2.4). I will, however, use the term misconceptions when I talk about students' alternative conceptual understandings in the remainder of this licentiate thesis.

Articles that try to problematize the teaching and learning of conceptual understanding in physics have been published by several authors. For example, Hewitt (1983) and van Heuvelen (1991) discuss the need to change our teaching to better meet our students' needs. Hewitt, now widely known for his teaching of conceptual physics, using his popular short videos "Hewitt-Drew-It"[11], stresses that students should primarily be able to explain the world around them before they try to calculate anything. Further, Linder (1992, 1993) was one of the first to problematize how the teachers' epistemological beliefs may influence students' conceptual learning. In these articles, Linder, amongst all, propose that conceptual understanding is the understanding *of something* (as suggested by the phenomenographic perspective, see Section 3.2) and that this conceptualization needs to be referred to a given context.

2.2.2 Instructional material

The implications of many of the earlier studies on conceptual difficulties resulted in needs to change the physics curriculum and instructional material. Many of these emphasise the interactive component in teaching and learning as compared to the "traditional lecture" (Docktor & Mestre, 2014). During the 1980s this was brought forward by, for example, Tobias (1986) who in a well-cited article described how non-science faculty experienced introductory physics lectures in an attempt to improve physics instruction to make it more accessible to all students. Some of the faculty attending these lectures reported on the passivity of the students, where the teacher didn't seem interested in questions or engagement with their students. This might have encouraged researchers to study the *interactive engagement* (IE) between teacher and students and how IE can increase the understanding of physics.

Throughout the years several areas of curriculum materials have been developed often directly from research on students' conceptual challenges. Among the lecture directed development are the *Just-in-Time Teaching* (JiTT) (Novak, Patterson, Gavrin, & Christian, 1999) and *Interactive Lecture Demonstrations* (ILD) (Sokoloff & Thornton, 1997). Lecture directed materials are focused on students' active participation through teacher-student interaction or student-student interaction (Docktor & Mestre, 2014). Other curriculum materials are focused on student interaction during laboratory work or recitations. Examples include both *Tutorials in Introductory Physics* (McDermott & Shaffer, 2002), focused on students interactive engagement during recitations, and *Interactive Science Learning Environment* (ISLE) (Etkina & van Heuvelen, 2007) who promote interaction in laboratory settings. A widely used resource for an overview of research-based curriculum material is the book

[11] http://www.hewittdrewit.com

Teaching Physics with the Physics Suite (Redish, 2003b). The book presents several curriculum materials and also includes a chapter on cognition and student learning (see also Section 2.2.4).

Although IE materials are widely seen as improving the students' conceptual knowledge and student learning, it doesn't come without discussion and critique. The most comprehensive study to investigate the conceptual gains in IE, was conducted by Hake (1998) who studied the increase of conceptual understanding using results from different conceptual assessment instruments (see Section 2.2.3) from more than 62 courses over the United States. Hake concluded, based on students' pre/post-tests, that IE is more effective in increasing students' understanding compared to traditional teaching. However, Turpen and Finkelstein (2009) has shown that incorporation of IE, through *Peer Instruction* (PI) (Crouch & Mazur, 2001; Mazur, 1997, 2009), in the classroom, doesn't automatically entail that it will be used in the same way everywhere, creating diverse learning opportunities for students. In a case study of how two professors apply PI in their classroom, they found that the different ways in which the two professors engaged with the students during PI suggested that the professors placed different emphasis on sense-making in their classroom. The inclusion of IE methods is, thus, not a single recipe for success.

Further, Henderson, Dancy, and Niewiadomska-Bugaj (2012) reports on different variables that has an effect on the faculty's use and implementation of research-based instructional methods in instruction. Additionally, Henderson and Dancy (2009) showed that many instructors at university level, although knowing about these resources, don't use them, or they make substantial modifications to their appearance.

2.2.3 Assessment instruments

From the extensive research on students' conceptual understanding a new focus on assessing students was developed in PER. Several assessment instruments are developed and used specifically for measuring and assessing students' conceptual understanding. In a study from 2017, Madsen, McKagan, and Sayre (2017) reports that over 40 different assessment instruments have been developed in physics and astronomy. They further showed (Madsen et al., 2017) that one of the earliest instrument, the Force Concept Inventory (FCI) (Hestenes, Wells, & Swackhamer, 1992), is known and used by a large proportion of physics faculty worldwide in their teaching. However, instructors are often unsure of how to incorporate these instruments in their teaching (Madsen, McKagan, Martinuk, Bell, & Sayre, 2016) and need guidance for how to do so effectively. Research-based assessment instruments are available in many different areas (Table 1) of physics and astronomy[12], however, mostly focus on introductory level physics and astronomy.

Assessment instruments like the ones in Table 1 can be used in multiple ways. Often, they are used as pre/post-tests to evaluate students' conceptual understanding. Docktor and Mestre (2014) write that students' results on concept inventories are used to compare students across populations and also to help understand the relationship between students score on, for example, the FCI, to their overall grade in the course.

Table 1. Selected examples of research-based assessment instruments. Inspired by Madsen et al. (2017).

CONTENT AREA	CONTENT	EXAMPLES
Mechanics	Kinematics	FCI (Hestenes et al., 1992)
	Kinematics	FMCE (Thornton & Sokoloff, 1998)
	Kinematics	MBT (Hestenes & Wells, 1992)
	Energy	EMCS (Singh & Rosengrant, 2003)
Electricity and magnetism	Electrostatics and magnetism	BEMA (Ding, Chabay, Sherwood, & Beichner, 2006)
	Electrostatics and magnetism	CSEM (Maloney, O'Kuma, Hieggelke, & Van Heuvelen, 2001)
Astronomy	General astronomy	TOAST (Slater, 2015)

2.2.4 Cognitive psychology

Much of the research within physics education has been situated within the area of conceptual difficulties and how this can be used to reform the curriculum of physics. However, more and more attention has also been given to students' cognitive resources for learning physics. Early contributions in this area come from Hammer who studied students' different approaches to learning physics (Hammer, 1989). Hammer noted how students either wanted to make sense of the content, or they wanted to be able to do the calculations and apply the equations. Elby (2001) expanded on these results and suggested instructional changes to increase students' epistemological beliefs, that is, their views about knowledge and learning. With the suggested changes to the curricula, focusing on the nature of knowledge and learning, Elby was able to show that students' understanding of physics increased as a result of these reforms.

Students' common-sense beliefs about physics, sometimes naïve ideas about how the world works, have been investigated by, for example, Halloun and Hestenes (1985a, 1985b). They claim that through traditional instruction, students' common-sense beliefs are not challenged and thus not changed, since teachers often are not aware of

[12] A more comprehensive list of available and reviewed assessment instruments can be found on PhysPort (https://www.physport.org/assessments/).

that they exist. Through their study, they found that students' initial knowledge highly influences their performance on the course. Studies, such as this, were frequent in the early 1980s and many attempts have been done to investigate students' conceptual frameworks in various parts of the physics curriculum (see e.g. Driver & Erickson, 1983). These frameworks are commonly referred to as *alternative conceptions* or *preconceptions* of a particular physics phenomenon and is thought to be described as a robust line of reasoning. diSessa (1988) has been critical to this and suggests that students' reasoning is not always as robust but can show in more weak and fragmented elements and call those *phenomenological primitives* (p-prims). diSessa's ideas have been challenged by, for example, Marton (1993) who, although agreeing with parts of diSessa's thoughts, does not agree with the idea of p-prims being mental structures[13].

Other epistemological resources have been investigated by, for example, Lising and Elby (2005) who aimed at reporting on how students' epistemological beliefs influence learning (see also, Hammer & Elby, 2003; Hammer, Elby, Scherr, & Redish, 2005; Redish, 2014). For example, how students' previous experience of a situation or context will influence their understanding of how to act can be described by how students *frame* the situation (Hammer et al., 2005) or by the situation's *relevance structure* (Marton & Booth, 1997, see also Section 3.2.1). To 'frame' a certain situation or event means to "interpret it in terms of structures of expectations based on similar events" (Hammer et al., 2005, p. 98). Framing is a central piece of the *resources framework* which is a theoretical framework developed within PER (Hammer, 2000; Hammer et al., 2005; Redish, 2003a). In this framework the epistemological units are known as *resources* which each student activates in a particular learning situation. The learning here is seen as a "cognitive state the learner enters or forms at the moment, involving the activation of multiple resources" (Hammer et al., 2005, p. 93).

2.2.5 Attitudes and beliefs

Students' learning is not only affected by their thinking about learning, but also by their expectations and attitudes towards physics and physics learning. In this regard, Redish, Saul, and Steinberg (1998) have contributed to the body of research by investigating students' expectations towards learning physics which resulted in the Maryland Physics Expectations (MPEX) survey. It is important that teachers obtain awareness of differences between teachers' and students' expectations, in order to provide students with epistemological tools for increasing their understanding. In the context of science education, both Tytler and Osborne (2012), and Osborne, Simon,

[13] Additional discussion about the differences between the alternative conceptions' framework and the p-prims idea can be found in Hammer (1996b, 1996a).

and Collins (2003) are reviewing available research on students' attitudes towards science. For a compilation of popular surveys on students' attitudes and beliefs, see Table 2.

Although there are plenty of research around students' attitudes and beliefs, since this area is out of my focus, I have chosen to leave this topic largely untouched.

Table 2. Collection of commonly used research-based surveys on students' attitudes and beliefs[14]. Inspired by Docktor and Mestre (2014).

TOPIC	TYPE	EXAMPLES
Attitudes	Likert-scale	MPEX (Redish et al., 1998)
	Likert-scale	CLASS (Adams et al., 2006)
	Multiple choice	VASS (I. Halloun, 1997; I. Halloun & Hestenes, 1998)
Epistemological beliefs	Likert-scale and multiple choice	EBAPS (White, Elby, Frederiksen, & Schwarz, 1999)

2.2.6 Representations in PER

The search for understanding how students interpret and use representations in physics teaching and learning has been a vital part of PER for many years. In this thesis I take the position that representations can include, for example, mathematics, diagrams, graphs, gestures, and spoken and written language[15]. McDermott, Rosenquist, and van Zee (1987) reported more than 30 years ago about students' difficulties connecting different representations of phenomena in physics, for example, connecting graphs to problem solving. Questions about the use of different representations in physics problem solving have previously also been raised by others, e.g., Beichner, 1994; Dufresne, Gerace, & Leonard, 1997; and van Heuvelen, 1991. A concrete example can be found in Van Heuvelen and Zou (2001) who studied how a multi-representational method using a combination of different representations was applied when teaching work-energy processes. In the context of astronomy, Eriksson, Linder, Airey, and Redfors (2014a) observed large discrepancies in what students and more experienced astronomers discern – what they notice and focus on – when viewing a particular representation. Eriksson (2014, 2019) brought his forward into the *anatomy of disciplinary discernment* (ADD), showing different levels of disciplinary discernment in general and for multidimensional thinking in particular.

[14] A more comprehensive list can be found at https://www.physport.org.

[15] In the theoretical framework of social semiotics, the term representation is often replaced by "semiotic resources". However, semiotic resources carry a somewhat different meaning than the, in PER, more commonly used term "representations", see Section 3.1 for a lengthier discussion.

In problem solving, students use different representations and research has showed what difficulties students encounter when working with them. In the use of mathematics in physics problem solving, Redish and Kuo (2015) studied how mathematics are used in physics teaching and learning, and Govender (2007) studied how students are applying algebraic signs in their vector calculations in kinematics. Also, the role of gestures for making sense of physics has been studied by, for example, Gregorcic, Planinšic, and Etkina (2017), Scherr (2008), as well as Euler, Rådahl, and Gregorcic (2019).

In physics problem solving, students are also required to be able to use multiple representations simultaneously. This ability is often taken for granted by instructors (Meltzer, 2005) but needs to be addressed in order to help students make *transductions* (see Section 3.1.3) between representations. Many studies have investigated the difficulties students encounter when introduced to multiple representations in physics problem solving and how they use them (see, for example, Finkelstein et al., 2005; Kohl & Finkelstein, 2006a, 2006b; Kohl, Rosengrant, & Finkelstein, 2007; Roth & Tobin, 1997; Tang, Tan, & Yeo, 2011). Further, Kohl and Finkelstein (2008) investigated expert and novice use of representations in problem solving and found that both students and also more experienced physicists use multiple representations in similar ways in their problem solving. However, although research is showing students' difficulties understanding and using different representations, these difficulties are not always transparent for teachers. Also, in other cases lecturers do not take this into consideration when teaching (A. Linder, Airey, Mayaba, & Webb, 2014; Tobias, 1986). In an attempt to survey students' representational fluency, Hill, Sharma, O'Byrne, and Airey (2014) suggested *the Representational Fluency Survey* (RFS) which was tested on university science students in Australia. Another example is De Cock (2012) who studied how students' problem-solving strategies was affected by the representational format used in the problem statement. She found that students employed different strategies when being presented with a verbal, pictorial and graphical presentation with isomorphic problem statements. As I have tried to exemplify here, learning with the use of multiple representations is a vital part of physics education, but at the same time a difficult competency for students to master. To deal with this challenge, Ainsworth (2006) proposed a special framework for learning with 'multiple external representations' (MERs). In most of the examples described here, the representations used are disciplinarily constructed, i.e. stem from the discipline. However, students-generated representations should also be considered in terms of providing insights into students' learning (e.g., Hubber, Tytler, & Haslam, 2010; Prain & Tytler, 2012; Prain, Tytler, & Peterson, 2009).

How teaching and learning of physics meet the difficulties of multiple representations has been further explored by for example Airey and Linder (2009, 2017), Linder (2013), and Fredlund, Airey, and Linder (2012) who investigated a way of introducing *social semiotics* into PER (see also Section 3.1). This way of looking at the communicative practices in physics teaching and learning has been the main theoretical perspective for many PhD students in the PER group at Uppsala University (e.g., Airey, 2009; Eriksson, 2014; Euler, 2019; Fredlund, 2015; and Samuelsson, 2020). This way of looking at physics teaching and learning, from a social semiotic point of view, hasn't been looked at before and provides the PER field with valuable knowledge about the communication practices used in physics.

2.3 A broader view of PER

So far, I have given an overview of PER from an international perspective. However, a national and semi-international look at PER shows that this field (and particularly science education research) is a research area that is constantly expanding. One example of the increased interest and focus of PER in the Nordic countries can be seen from the Nordic Physics Days conference[16] (scheduled to be held in Uppsala later this year) where one of the main events of the conference is the work done in PER.

2.3.1 A Swedish (and Nordic) perspective of PER

As mentioned earlier in this thesis, groups that are situated at the physics department and that focus entirely on PER in Sweden are few. However, research on physics and/or science teaching and learning is being done at various universities and colleges in Sweden, but these groups are mainly situated at the department of education. Further, the majority of this work is also being focused on school-level, and not primarily on university level, which is where I tend to focus my work. Science education research in Sweden, mostly on school-level, is often published in the Nordic journal for science and technology education research, *Nordina*[17]. Nordina accepts contributions from researchers in the Nordic countries as well as from other countries. Papers are published in either Swedish, Danish, Norwegian or English. I am aware of the large body of science research in Sweden and the other Nordic countries, but since this research falls outside the scope of this thesis, I will keep this discussion here to a minimum.

[16] https://www.nordicphysicsdays2020.se

[17] https://journals.uio.no/index.php/nordina

In Sweden, the National Resource Center for Physics Education[18] (NRCF) at Lund University, has for more than 25 years been providing Swedish physics teachers and students with valuable inspiration and resources for teaching. Their mission is to provide resources to the teaching and learning of physics to teachers and students in all levels from pre-school (*förskola/förskoleklass*) to upper secondary school (*gymnasium*). Over the years, NRCF has also been publishing research results on various topics such as the nature of science (e.g., Hansson & Ledén, 2016) and playground physics (e.g., Pendrill et al., 2014a, 2014b).

In Sweden and the other Nordic countries, the phrase 'physics education research' is often translated into *physics didactics*, however, the appropriate Swedish term for PER would be 'Fysikdidaktisk forskning'. The word 'didactics' originates from the Greek word *didaskein* which means 'to teach' and was first used in the 17th century (Merriam-Webster, n.d.). It is worth noticing that the word 'didactics' has a different association in the Nordic countries (and also in countries such as Germany where 'Physikdidaktik' is a widespread research area) compared to, for example, the US. Instead of pointing to the art of teaching, didactics in a Nordic sense has a more theoretical connotation but varies somewhat between countries and universities.

2.4 My position in PER

In the previous few sections, I have tried to lay out my view of the field of PER and to give an overview of the existing work in different parts of this field. A relevant continuation is then to describe how I find myself to be positioned in relation to the work already mentioned above. In this thesis I will first and foremost contribute to the PER literature by working on theoretical perspectives on understanding students' learning challenges in introductory physics. This theoretical perspective, known as social semiotics (see Section 3.1) is mostly related to students' use of, and communication through, different representations (i.e. *semiotic resources*) which is why my work will add to the body of work in this part of PER. I especially find my work to contribute to the understanding of student' communicative practices during collaborative group work among students.

Having laid out my interpretation of pertinent PER and given an overview of the existing literature, and discussed my own position within this interpretation, I will spend the next section of this thesis describing in a more detailed way the theoretical frameworks that have framed my research for this licentiate thesis.

[18] http://www.fysik.org

3 Theoretical frameworks

In the work presented in the papers that make up this thesis I have made use of different theoretical frameworks for analysing the data. My aim with this chapter is to provide an overview of these theoretical frameworks, as well as a more detailed description of the main elements that is important to understand for my analysis. In this chapter I do not aim to present how I applied these frameworks in an empirical way. Instead I will leave the empirical application to a later chapter (Chapter 4).

The theoretical frameworks that have guided my research and analysis are variation theory and social semiotics. I will introduce social semiotics and the key elements that I have used in Section 3.1. Variation theory will be introduced in Section 3.2.1. However, since variation theory was developed from phenomenography, I will start Section 3.2 by introducing phenomenography and continue with the transition to variation theory. An overview of phenomenography is also needed to be able to understand the basis of the analysis used for Paper I.

3.1 Social semiotics

The study of how meanings are negotiated between people and in what ways they use various means for communicating is referred to as *social semiotics* (see, for example, Hodge & Kress, 1988; Kress, 2010; Lemke, 1990; van Leeuwen, 2005). This approach stems from the study of signs ("semiotics") and how we make meaning of signs, where signs in a broader perspective can be, for example, gestures, diagrams, images, tools, and actions. Social semiotics studies how people use and interpret these signs in their communication, and how signs are used to make meaning in a specific social context or community, such as physics or astronomy. I am choosing to adopt Airey and Linder's definition of social semiotics as "the study of the development and reproduction of specialized systems of meaning making in particular sections of society" (2017, p. 95). Within the social semiotics framework it is stressed that signs in themselves don't have meaning in their own, but meaning is made in the context which they are in (Section 3.1.3, see also Lemke, 1990). Further, a certain sign can be interpreted to have different meanings, and the same person can make different meanings of the same sign depending on context, previous experiences etc. Lemke, who in his book "Talking Science" (1990) brought the social semiotic analysis into communication within the science discipline, further suggests that humans "do not so much "discover truths" as we construct meanings" (1990, p. 185, emphasis his) and states that this constructed meaning may differ between different communities. Every community has its own particular system of "meaning-making (i.e. semiotic) practices" (p. 187). Thus, to be part of the community we need to learn how to use those practices in meaningful ways.

3.1.1 Multimodality

This social semiotics framework is an example of an approach to research on multimodality (Jewitt, Bezemer, & O'Halloran, 2016; Kress, 2010). What 'multimodality' really is about varies and have probably several meaning to different researchers. But, as Jewitt et al. (2016) explain,

> Multimodality questions that a strict 'division of labour' among the disciplines traditionally focused on meaning making, on the grounds that in the world we're trying to account for, different means of meaning making are not separated but almost always appear together: image with writing, speech with gesture, math symbolism with writing and so forth. It is that recognition of the need for studying how different kinds of meaning making are combined into an integrated, multimodal whole that scholars attempted to highlight when they started using the term 'multimodality'. It was a recognition of the need to move beyond the empirical boundaries of existing disciplines and develop theories and methods that can account for the ways in which we use gesture, inscription, speech and other means together in order to produce meanings that cannot be accounted for by any of the existing disciplines. (Jewitt et al., 2016, pp. 2–3)

Put in a simple way, multimodality deals with the arrangement of multiple (semiotic) resources. In multimodality, the resources used for meaning making are often grouped together in certain 'modes' which are "socially shaped and culturally given semiotic resource[s] for making meaning" (Kress, 2010, p. 79). Today there have been several examples of how to use a multimodal approach to teaching and learning. For example, Kress, Jewitt, Ogborn, and Tsatsarelis (2014) studied teaching and learning in the science classroom from this multimodal perspective, and Bourne and Jewitt (2003) studied English literacy in a school classroom.

In the development of social semiotics Kress and van Leeuwen (2006), drawing on the multimodal framework, has been trying to shift the focus from linguistics into the field of visual representations. Their view is that it is possible to analyse images in similar ways as written text. In a similar way as when reading a written text, where one can ask the question "how do people read this text?", images can also be thought of as asking the question “how do people read these images?”. Kress and van Leeuwen’s ideas can be used to better understand how visual representations are constructed and how people therefore get to read the signs. Reading and interpreting these visual representations will become more and more important as we progress in our modern, visual world. As an example, Bezemer and Kress (2008) show how visual representations in a school textbook can be interpreted and understood in multiple ways by analysing images in textbooks from mathematics, English and science. In a Swedish context, Lagerholm (2020) studied how representations are used to communicate the concept of ‘pressure’ (sv. *tryck*) in secondary-school physics textbooks. She found that many visual representations used in these textbooks on their own can’t provide students with enough guidance, but needs additional focus through teaching, if students are to fully grasp the physics content which they represent. Additionally, the interrelationship between representations used in these textbooks is often not made explicit.

Kress and van Leeuwen’s visual, multimodal framework is used in various other contexts as well, for example, in science where Tang, Delgado, and Moje (2014) used the framework to analyse children’s visual demonstrations of a science phenomenon. In their study they combined multiple representations analysis with a multimodal analysis of children’s representations in a particular science context. In order to provide students with effective teaching, teachers need to know how, not only texts and speech, but also how images and other visual representations are interpreted, and how students’ own visual interpretations may be used to understand their ideas.

3.1.2 Semiotic resources

A central focus in social semiotics is the use and understanding of so called *semiotic resources*. Airey and Linder (2017) suggests a way of defining the different types of communicative resources for a certain discipline, a disciplinary discourse. They propose that the communication in each discipline can be divided into certain *semiotic systems* (i.e. ‘modes’, see above). In a physics context, examples of different semiotic systems may include, but is not limited to, spoken and written language, gestures, mathematics, apparatus, and pictures (Figure 1). Additionally, each semiotic system is made up of a variety of semiotic resources—resources that are used for communication and meaning making within that social group. In this thesis I am adopting Airey and Linder's (2009, 2017) view of semiotic systems and semiotic resources which has been developed from the work of van Leeuwen. van Leeuwen (2005, p. 3) defines semiotic resources “as the actions and artefacts we use to communicate, whether they are produced physiologically – with our vocal apparatus; with the muscles we use to create facial expressions and gestures, etc. – or by means of technologies – with pen, ink and paper; with computer hardware and software; with fabrics, scissors and sewing machines, etc." This means that representations often used in physics, such as written and spoken language, mathematics, graphs, diagrams, and apparatus, are treated as semiotic resources by the definition used by van Leeuwen.

In a learning situation, students are required to make sense of the disciplinary semiotic resources used to gain access to the *disciplinary relevant aspects* (DRAs) related to the phenomenon or task at hand. Such DRAs are "those aspects of physics concepts that have particular relevance for carrying out a specific task. Thus, disciplinary-relevant aspects in physics are those aspects that physicists would draw on in order to solve a particular problem or explain a given phenomenon" (Fredlund et al., 2015, p. 2). This means that in any situation, for a disciplinary concept, there are only a limited number of DRAs that will be relevant. To exemplify what they mean, Fredlund et al. (2015) used the concept of refraction of light and gave examples of potential DRAs, including distance, medium, refraction index and sine of angle. They further note that only a subset of them will be relevant in order to solve a particular problem. It is therefore critical that students, in a learning situation, is given the appropriate tools to be able to discern these DRAs. This discernment can be enhanced by the use appropriate variation (see Section 3.2.1) to gain access to the DRAs.

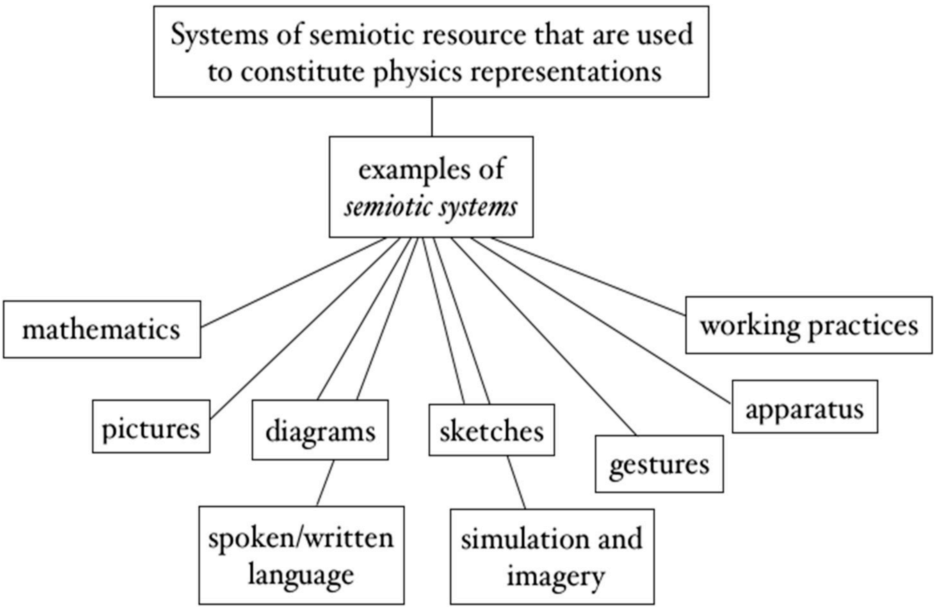


Figure 1. A diagrammatic overview of examples of semiotic systems within the discipline of physics. Adapted from Airey and Linder (2009).

In PER, semiotic resources are often used interchangeably with the more commonly used term representations but could in fact be divided into three parts; representations, tools and activities (Airey & Linder, 2009). Examples of 'tools' used in physics are, an oscilloscope and a low friction air track, while examples of activities are the working practices used in a physics laboratory. In this thesis I will focus on representations and would like to point out two different types of representations; *persistent* (e.g. diagrams, written language, and images) and *non-persistent* representations (e.g. gestures and spoken language). The use of persistent representations and how they can aid students in their learning process have been studied by, for example, Fredlund et al. (2012), who studied how students shared knowledge through the use of persistent representations in the context of optics. Another example is Volkwyn et al. (2018) who showed that a persistent representation in the form of a cardboard arrow could be used by the students as a 'coordinating hub' (Fredlund et al., 2012) around which to structure their discussions when learning about the Earth's magnetic field. An example of a study of a non-persistent representation is Euler et al. (2019) who used their understanding of students' embodiment (which can be linked to the semiotic system of 'gestures') to analyse a learning situation between students learning about a binary star system.

In physics problem solving, some of the most frequently used semiotic systems may include mathematics, diagrams, and different types of images. However, the use of other semiotic systems in physics teaching and learning has been given more and more attention of the last few years. For example, Eriksson, Linder, Airey, and Redfors (2014b) studied how the discernment of DRAs differed between experts and novices using a video simulation. In another study, C. R. Samuelsson, Elmgren, Xie, and Haglund (2019) used a combination of social semiotics and the resources framework (Hammer et al., 2005; Redish, 2003a) to analyse the way students and instructors were able to explain the concepts of evaporation and condensation when observed through an infrared camera.

In a Swedish context, Axelsson, Danielsson, Jakobson, and Uddling (2017) used a social semiotics framework in their study of how the use of multiple semiotic resources could assist multilingual students to learn science in a Swedish elementary school. They found that both students and teachers used several different resources in their communication and learning process which was found to be fruitful for learning. The use of multiple semiotic resources in problem solving has also been studied by Weliweriya, Sayre, and Zollman (2019) who observed how a student made use of multiple semiotic resources to help him solve a problem in electromagnetism. In an example from chemistry, Danckwardt-Lillieström, Andrée, and Enghag (2018) analysed how creative drama as a form of semiotic system could be used to enhance students' learning of intermolecular forces. They concluded that this way of approaching the topic presented new ways of exploring this context especially when used together with other semiotic resources.

While it is crucial that students learn how to make use of the disciplinary representations that are used in the discipline, one also has to be able to discern the disciplinary relevant information from a certain representation. Eriksson et al. (2014a, p. 170) refers to the importance of "reading" representations—a *disciplinary discernment*—which they define as "noticing something, reflecting on it, and constructing meaning from a disciplinary perspective". Any representation used in teaching must be "read" by the student and it is often so that novices of do not see the same things in a representation as the experts do (U. Eriksson, 2014, 2019). Therefore, disciplinary discernment becomes crucial to learning; the teacher needs to find out what the students discern and use that information to plan their teaching (cf. Ausubel, 1968).

In physics, as in any discipline, it is crucial that students get to understand and appreciate the use and potential meanings of each of the relevant disciplinary resources that the discipline make use of, which brings me to my next important theoretical construct: *affordances*.

3.1.3 Affordances

In the late 1970s, Gibson (1977, 1979) introduced the idea of *affordances* which pointed to what the environment could 'afford' animals or organism in a given system. According to this definition by Gibson, the affordance is inherent with an object itself and can be seen as a relationship between the object and the 'actor' (for example, a person or an animal). While Gibson was not pointing specifically at the affordances of a meaning making representation or activity, this idea has been introduced into the work of social semiotics. The way I use affordance in this thesis draws on the work of Gibson, which has been further developed by Kress and colleagues:

> Several issues open out from this starting-point: if there are a number of distinct modes in operation at the same time (in our description and analysis we focus on speech, image, gesture, action with models, writing, etc.), then the first question is: 'Do they offer differing possibilities for representing?' For ourselves we put that question in these terms: 'What are the *affordances* of each mode used in the science classroom; what are the potentials and limitations for representing of each mode?'; and, 'Are the modes specialized to function in particular ways. Is speech say, best for this, and image best for that?' (Kress et al., 2014, p. 1, emphasis theirs)

That is, affordances of a semiotic resource points to the strengths and potentials for meaning making of this semiotic resource (see also van Leeuwen, 2005). It is worth noticing the difference between how Gibson originally defined affordance, and how

Norman (1988) later used the concept. While Gibson thought of the affordance being an inherent property within the object, Norman suggested instead to use the term affordance as set by the user and may change depending on the context and the person viewing it and pointed specifically at the 'perceived affordance' (Norman, 1988, 1999).

The idea of affordances used in social semiotics directs the focus to the collective meaning making potential, for example, when used as a way of communication, where each semiotic resource has their own specific affordance. This means that it is important for students to understand how each specific semiotic resource can be used to share the appropriate disciplinary meaning for the context in question and how a combination of resources can work together to generate a 'collective affordance' (Linder, 2013), also known as a 'critical constellation' of semiotic resources (Airey & Linder, 2009)[19]. Such disciplinary meaning potential mentioned here is referred to as the *disciplinary affordance* for that semiotic resource (Airey & Linder, 2017; Fredlund et al., 2012). Fredlund et al. (2012, p. 658) defines disciplinary affordance as the "inherent potential of a [semiotic resource] to provide access to disciplinary knowledge". Airey, Eriksson, Fredlund, and Linder (2014) stress that it is only when there is a match between what a semiotic resource might afford a student and the particular disciplinary affordance, that learning is possible. However, students may discern a different disciplinary affordance for a particular semiotic resource and hence Eriksson et al. (2014a, p. 170) define the *discerned disciplinary affordance* as "a subset of the total disciplinary affordances, set by the discipline community, of that representation". In the context of teaching and learning, one can also talk about the pedagogical usefulness of a semiotic resource—the *pedagogical affordance*. This is defined as "the aptness of a semiotic resource for the teaching and learning of some particular educational content" (see Airey & Eriksson, 2019, and the references therein). Notice that while the disciplinary affordance stays somewhat fixed, the pedagogical affordance of a semiotic resource is dependent on the student experiencing that resource in a given context. Having laid out the definitions of pedagogical and disciplinary affordance, it is worth noticing the relationship between the two. As Airey and Linder (2017) suggests, which is later developed by Airey and Eriksson (2019), there can be an inverse relationship between pedagogical and disciplinary affordance: the pedagogical affordance can be increased by, for example, unpacking the disciplinary affordance within the resource. At the same time, the disciplinary affordance will usually (but not always) be decreased. Airey and Eriksson (2019) discuss the need for taking pedagogical affordance into account when teaching about the HR-diagram in astronomy. They suggest that since this diagram has

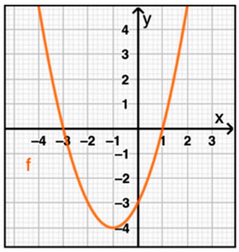
[19] An example of a collection of semiotic resources that might provide such 'collective affordance' is given by van Heuvelen (1991).

a high level of disciplinary affordance, and a low level of pedagogical affordance, it makes the content hard to access for beginning astronomy students.

Translations of semiotic resources

As I have just introduced, different semiotic resources offer different disciplinary affordances. Therefore, an important ability within each individual discipline is to be able to make *translations* between semiotic resources and semiotic systems in order to use and understand the most apt resource(s) for the particular context. These translations are referred to as *transduction* (meaning is shifted across systems) or *transformation* (meaning is shifted within the same semiotic system) (see Figure 2 and, Bezemer & Kress, 2008; Jewitt, Bezemer, & O'Halloran, 2016). In physics problem solving these abilities are constantly being asked for by the discipline. An example is given by van Heuvelen (1991) who shows how students are expected to be able to translate between text, picture, physical representation, and mathematics in the same problem. Volkwyn, Airey, Gregorcic, and Heijkenskjöld (2019) showed in another example how using a handheld device could assist students in making a transduction of the Earth's magnetic field onto a cardboard arrow, a persistent representation (see Section 3.1.2). However, although the translations will hopefully make new information or aspects of the phenomenon visible, it is inevitable that some information may also be lost in the process (Bezemer & Kress, 2008; Bezemer & Mavers, 2011).

$$y = (x + 3)(x - 1) \Longrightarrow$$



$$y = (x + 3)(x - 1) \Longrightarrow y = x^2 + 2x - 3$$

Figure 2. Figure showing a transduction (top row) across the semiotic system 'mathematical equation' and 'graph', and transformation (bottom row) within the semiotic system 'mathematical equations'.

3.2 Phenomenography and the development of variation theory of learning

Within education research, focus has historically been on *what* students actually learn, and what difficulties and challenges to learning that they face. In the mid 1970s, however, Marton and colleagues at Gothenburg University started to turn their interest towards how students learned instead by starting out with asking the question; *how* (or *in what ways*) do people go about learning (e.g., Dahlgren & Marton, 1978; Marton, 1981). Säljö (1979) was in an early study able to identify that some people see learning as something that is taken for granted (more or less rote learning), while others see learning in a more thematized way, i.e. that "learning is something which can be explicitly talked about and discussed and can be the object of conscious planning and analysis. In learning, these people realize that there are, for instance, alternative strategies or approaches which may be useful or suitable in various situations depending on, for example, time available, interest, demands of teachers and anticipated tests" (Säljö, 1979, p. 446). This approach to understanding the experience as described by others (a second order perspective) was named *phenomenography* (Marton, 1981). In this perspective 'reality' is not 'out there' waiting to be uncovered. Instead 'reality' is seen as being made up by the relation between the phenomenon and the person (a *non-dualistic* approach).

Phenomenography was developed from an inquiry aimed to understand how people experience a phenomenon (Marton, 1981). Only by understanding peoples experience of a phenomenon can you understand how they will act on the same phenomenon (Marton & Booth, 1997). That is, phenomenography is interested in people's experiences rather than their behaviour, although these aspects often are intertwined. Further, the researcher here aims to understand the descriptions of phenomenon that are given. In the development of phenomenography, the main inquiry was to find experiences for learning. In this sense, it is important to understand the learning is being able to discern, not only to 'see' something. To *discern*, according to Marton and Booth (1997), means that one is able to see the relation between the parts of the phenomenon and the whole, and how the whole relates to the context. An example of this relationship is given by Lo:

> The parts and whole refer mainly to the structure of an object. For example, if we look at a man as a 'whole', then his eyes, ears, mouth, nose, hands, legs, etc. are parts of the whole. If a man saw a pair of eyes in dark woods and recognised them as the eyes of a deer, then this would mean that he had already discerned the structure of a deer, its eyes relative to its other parts, such as its mouth and nose, and its whole (the face of a deer and the profile of its body). (Lo, 2012, p. 57)

The main outcome of a phenomenographic study is a set of qualitatively different categories that make up the *outcome space* of the different ways a certain phenomenon is experienced by a group of people. This categorization process follows a naturalistic approach (Lincoln & Guba, 1985) where the categories emerge from an iterative categorization process (see Section 4.2.1), for example through a 'constant comparative method' as described by Glaser and Strauss (1967)[20]. It should be noted, as Lincoln and Guba (1985) does, that the constant comparative method was introduced as a process for a grounded theory[21], not necessarily a way of analysing data. With this in mind I want to remind the reader that phenomenography is not a research method *per se*. Instead it is an approach to understanding the results obtained from the categorizing of the available data. The outcome space of different experiences has an inherent hierarchical distribution, spanning from the least advanced way of experiencing the phenomenon to the most advanced way. This hierarchical distribution can often be thought of as an analogy to Russian 'babushka dolls' where the smaller dolls fit inside the bigger dolls. This hierarchy is based on the disciplinary way of viewing the phenomenon and is dependent on the interpretation of the researcher and his or her background knowledge and experience (see Chapter 4, and, for example, Butler, 1998).

From the categories of description of peoples' experiences, it follows that people are aware of different things of a certain phenomenon. This is referred to as the *anatomy of awareness*[22] (Marton & Booth, 1997). From this it follows that a person is only able to focus on a few aspects at a time and that it is impossible for a person to experience all aspects of a phenomenon the same way at all time. One can understand this in terms of what is in the person's *focal awareness*. Focal awareness can be understood in terms of Gurwitsch's (1964) concept of "the theme"—what is being focused on or what is the intended object of learning (Lo, 2012). At any given time there are three different levels to our awareness; the theme, the thematic field, and the margin (e.g. Booth, 1997; Marton & Booth, 1997). Using an example question— "A cyclist is cycling straight forward at a high constant speed on a road. What forces act on the bicycle?"—from a

[20] This seemingly "obvious" similarity between the "phenomenographic method" and grounded theory has been discussed by other authors. One example is Richardson (1999) who develops this comparison and also notes that Säljö (1982) in his early phenomenographic work referred to Glaser and Strauss' method in describing his own way of doing the analysis.

[21] Although there is much to be said about the development of grounded theory and the similarities to the phenomenographic categorization, I will keep this discussion short for the purpose of this thesis. In Section 4.2.1 I will describe the categorization process used in phenomenography but will keep the discussion regarding grounded theory and the development of this process to a minimum, since this is beyond the scope of my thesis.

[22] The anatomy of awareness can be used to understand a person's *relevance structure* (see below).

study by Svensson and Högfors (1988), Booth (1997) discuss these three levels of the anatomy:

> From the field of ideas which this statement conjures up, some theme will emerge, the focus or object of the thinkers' awareness. In that force is the object of the question, that might be the initial theme. "Force", the theme, is figural in awareness, and associated with the theme there are other aspects of the problem, related by some relevance to the theme. Here we might expect to find notions about motion, constant speed, velocity and acceleration, motive and retarding forces, the force of gravity, mass, weight, etc. While force is figural—the object of thought—this field of notions forms the background. We can say that force is the theme of awareness and all the rest form the thematic field. The items which are thematic constitute a gestalt, which is conjoined with the constituents of the thematic field through unity of context or unity of relevance. Then, the student is also certainly aware of non-relevant things which are present at the same time in the background, such as the time of day and the noise outside the window, or the lecture that has just finished, and these we can call the margin. (Booth, 1997, p. 141)

In this example, the intended object of learning is 'forces', thus this will be in the focal awareness for solving this problem. However, relevant for understanding the anatomy of awareness is also to consider things that are <u>not</u> in a person's focal awareness. Aspects that are not in focal awareness can either be *transcended* (overlooked or not noticed at all) or *taken-for-granted* (not even considered) (Marton & Booth, 1997).

Because people experience a phenomenon in different ways, they will also be able to learn in different ways depending on what aspects they have discerned. The development of these ideas leads to the development of a theory focused on how learning is constituted. This theory was at first introduced as the 'new phenomenography' (Pang, 2003) and is today referred to as the *variation theory of learning* (Marton, 2015). I have used several elements from variation theory in my research, which is why I will introduce this theory in the next section, as well as describe the elements that underpin my work that is presented in Papers I and II.

3.2.1 The variation theory of learning

The variation theory of learning was developed from the insights provided by phenomenography. This theory is concerned with the necessary conditions for learning and how they can be used in effective teaching (Marton, 2015; Marton & Booth, 1997; Marton & Tsui, 2004). The essence of this theory is that there are certain *critical aspects* of a phenomenon—an *object of learning*—that are necessary to be able to discern, and to contrast to other aspects of the same phenomenon, in order for someone to learn and understand the phenomenon. The necessary condition for this discernment is structured variations, i.e. "[t]here is no learning without discernment and there is no discernment without variation" (Marton & Trigwell, 2000, p. 387). This means that 'variation' and 'discernment' are important concepts for understanding what constitutes learning according to variation theory. However, an additional important concept is 'simultaneity. Marton (2015) writes that,

> [...] no discernment (of features or aspects) can happen without the experience of difference. But no difference can be experienced without the simultaneous experience of the things that differ. And two things cannot be experienced simultaneously—as two things—without being discerned. Discernment, difference and simultaneity are necessarily related to each other. None of them can exist without the others; they presuppose each other and hence cannot be temporally ordered. (p. 66-67)

Thus, variation, discernment and simultaneity are logically intertwined to be able to understand learning. For someone to learn something new—a new phenomenon—that person must experience variation to be able to discern a new aspect of this phenomenon, and at the same time, the person must discern this new aspect simultaneously with previously discerned aspects of the same phenomenon. Booth and Hultén (2003) summarizes this like this:

> "Variation" is an essential aspect of learning in this sense: that learning occurs (things are seen in distinctly new ways) when a dimension of variation opens around a phenomenon or aspect of a phenomenon that once was taken-for-granted. "Discernment" is the act of seeing this no-longer-taken-for-granted phenomenon or aspect of a phenomenon in a new light. "Simultaneity" – seeing both the once-taken-for-granted and the no-longer-taken-for-granted – is demanded for the dimension of variation to open. Lack of understanding is thus linked with being unaware of the potential for variation – seeing only that which is taken-for-granted. (p. 69-70)

The 'variation' referred to here is in regard to a specific aspect—a critical aspect—of that phenomenon. The critical aspect is a particular aspect that characterizes the object of learning, or the specific phenomenon. In variation theory, the critical aspects are also known as different *dimension of variation* (DoVs) (Lo, 2012, see also below). To be able to discern this critical aspect, and how it relates to the phenomenon, the person must be confronted with variation within this aspect in the form of different values of this aspect. These different values are known as *critical features* (see Figure 3).

Another important aspect of learning according to variation theory is that to be able to know what something is you also have to know what something is not—for example, to be able to know what a 'Persian cat' is, you also have to know what a 'Persian cat' is not. In terms of variation, discernment and simultaneity, this means that you need to experience variation within a critical aspect of a Persian cat (e.g. length of muzzle and length of coat) in order to discern this critical aspect as critical. At the same time, you need to discern the variation within these aspects simultaneously as exactly different values of an aspect (e.g. different length of muzzle). If, for example, all cats had the same length of their muzzle, you would not be able to discern this aspect as a critical aspect. This means that you will have to experience differences between different aspects against a background of sameness—keeping other aspects invariant. It is through this experience that you will be able to understand what constitutes the phenomenon, and what does not.

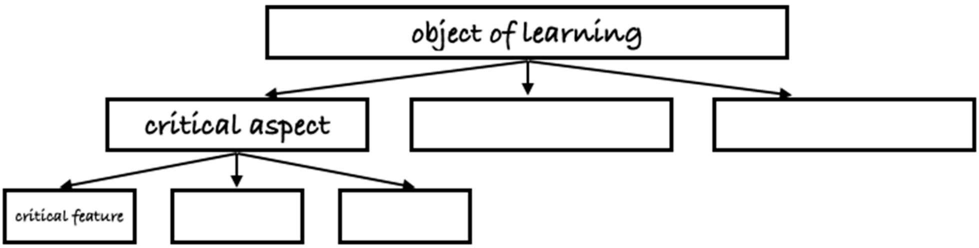


Figure 3. A diagrammatic scheme of the relationship between 'the object of learning', 'critical aspects' and 'critical features'. Each object of learning can have multiple critical aspects and not exactly three as pictured here. Similarly, each critical apect can have multiple critical features connected to it.

By generating this particular kind of variation—i.e. highlighting different critical features of a certain critical aspect—there is, however, no guarantee that learning will take place. Nonetheless, variation theory states that this variation is a necessary condition for learning to be possible (Marton, 2015).

In the following subsections I will elaborate on and expand the discussion around two critical concepts from variation theory that are of particular relevance to my work, namely *dimensions of variation* (DoVs) and *relevance structure*.

Dimensions of variation

As I have described in the above section, the central idea in variation theory is that in order to learn, you need to experience variation in regard to a certain critical aspect—a dimension of variation (DoV). Each dimension of variation can take different values—critical features—and it is when a person is presented with different values of this DoV, that they can discern a new aspect of the phenomenon. When a person experiences a feature in a given DoV for the first time, Marton (2015) refers to this as *opening a new dimension of variation*. Note that the person here has not yet experienced any *possible variation* in this dimension (see Watson and Mason, 2006). Further, Watson and

Mason (2006) suggests that when you are experiencing a new value of a dimension of variation (which have already been opened up), you are expanding the *permissible range of change* (see also, Goldenberg & Mason, 2008). For example, if a person is to learn the meaning of the word 'blue' (a dimension of variation) this dimension can be opened up by exploring a new value of the colour blue (Figure 4, top row). However, if the DoV already has been opened up, yet another new value in this dimension will expand the 'permissible range of change' (Figure 4, bottom row).

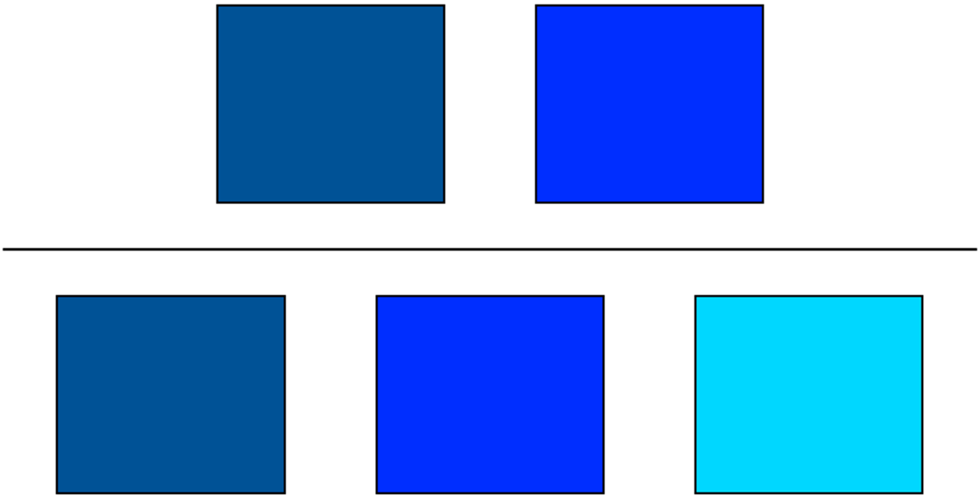


Figure 4. Example of opening a DoV (top row) and expanding the permissible range of change of a DoV (bottom row).

By experiencing variation within a DoV (i.e. experiencing new critical features), it is possible to place the varied aspect in the person's focal awareness. The person will then be able to discern this aspect and through at the same time experience this new aspect together with previously discerned aspects she will look at the aspects of the phenomenon in a different way. Two pertinent examples of how students are experiencing variation through the experience of new dimensions of variation are Booth and Hultén (2003) and Ingerman et al. (2009).

Booth and Hultén (2003) followed a web-based discussion among mechanical engineers as they were asked to discuss how to build an automated car. They noted that when new values of a DoV was being experienced, the person was able to discern a previously taken-for-granted knowledge and simultaneously discern this knowledge in relation to the no-longer taken-for-granted knowledge. In their case, a pivotal statement made by one of the participants was that the automated car should be able to drive in two different settings (city and highway traffic) and specified the different requirements for these settings. This statement opened up a DoV "about the range of functions the vehicle must have" (p.75). The participants were hence no longer able to take the functions of the car for granted.

A second example, that has relevance for this thesis, comes from Ingerman et al. (2009). They studied groups of university students who were learning about Bohr's model of the atom by working with physics problems using a computer simulation. The analytic approach of their study, drawing on variation theory, was to explore the variation that students experienced in the process of constituting learning. By analysing the students' discussions (video-with-audio recorded) they were able to identify two ways in which the students experienced variation: (1) variation *within* a critical aspect (i.e. dimension of variation), and (2) variation *across* critical aspects. They identified 'threads of learning' for each of these approaches and, based on their analysis, argued that learning and new understanding is created within these threads of learning.

The two examples given above show how students themselves create meaningful variation by exploring different DoVs in their particular contexts. Apart from these examples, most examples that can be found in the literature are focused on teacher-created variation—i.e. variation created from a disciplinary expert (e.g. Fraser, Allison, Coombes, Case, & Linder, 2006; Fraser & Linder, 2009; Linder, Fraser, & Pang, 2006; Lo, Chik, & Pang, 2006). The research presented in this thesis will, similar to the two examples given here, focus on student-created variation.

Before I move on to the next central aspect from variation theory, I would like to add a short commentary about the similarities between 'disciplinary relevant aspects' (DRAs) and 'critical aspects' (i.e. 'dimensions of variation', DoVs). In several occasions these constructs can be considered to be equivalent, however this relationship still needs further discussion which falls outside of the scope of this thesis. However, in this thesis I have tried to be consistent in my use of the appropriate term and suggest that a DRA will not be referred to as a DoV until a student has generated variation *within this DRA*, or a student has experienced any variation within this DRA. The variation being generated will then be known as experiencing *values of this DoV*.

Relevance structure

Within variation theory it is obvious that it is critical to understand how students will see, or experience, the learning situation. In regard to this, the concept of *relevance structure* (Marton & Booth, 1997) becomes an important concept. A person's relevance structure can be described as a relation between the person and the phenomenon. Marton and Booth (1997, p. 143) explains that "[e]ach situation, whether we consider it a learning situation or a situation in which one is applying something learned, has a certain *relevance structure*: the person's experience of what the situation calls for, what it demands" (emphasis in original). Thus, it is the person's relevance structure that decides how she sees the phenomenon, what she will find relevant for the situation, and further in what ways she will take on a specific problem. The idea behind relevance structure comes from Székely (1950) who in his study investigated how students acted in different ways when approaching the same physics task in different ways. In a recent study, Euler, Gregorcic, and Linder (2020) proposed to use the term *enacted relevance structure* when talking about the relevance structure as implied by students' choice of DoVs. Contemporary studies that focus on relevance structure are rare. Some of the very few examples that are relevant to the work presented in this licentiate thesis are Booth (2001); Domert, Airey, Linder, and Lippmann Kung (2012); and, McKenzie, (2002).

An example of how relevance structure is being used to understand a learning situation is given by Booth (2001). In this study, Booth explored computer science students' relevance structure for a particular course in their program. She found that students held three different views of the relevance for the course—i.e. three different relevance structures—and argued that only one of them were found to be consistent with the general aim for the course. Students who experienced any of the other two relevance structures were thought to not profit as much from the course and she further writes that "[t]he relevance structure for the students can only be brought about through tutor's experienced relevance" (Booth, 2001, p. 185). One can thus argue that the relevance structure can change through education, through aligning with the teachers' experienced relevance, which, in turn, is made possible through the experience of variation.

On the other hand, McKenzie (2002) presented results from a study involving teachers' view of teaching and learning. She found that teachers who perceived teaching in a particular way—a particular relevance structure for teaching—weren't able to change their way of teaching if the dimensions of variation to teaching that they were presented with didn't support what they found to be relevant for the situation, i.e. didn't match their relevance structure.

From the discussion in this chapter it is of interest to further study how students' relevance structure is structured and how it is possible to change through the experience of variation of critical features.

4 Methodology

Education research is often carried out in one of two possible ways; either a quantitative approach is taken to the research, or a qualitative. I have chosen to take a qualitative approach to my research, focusing on data which are non-numerical and relies more on the interpretation and perception of the researcher. The exact definition of qualitative research does not exist, but as Hammersley (2013, p. 2) puts it, it is about "the absence of quantification." Researchers in this approach are more interested in questions around 'why' and 'how', instead of 'how many' or 'how much'.

The research on which this thesis is built upon is what is referred to in the literature as 'case studies' (Baxter & Jack, 2008; Tellis, 1997). The definition of a 'case' and 'case studies' differ between disciplines, but Stake (1995), focusing on case studies in education research, focuses on the case being "a specific, [...] complex, functioning thing" (p.2). In a case study the researcher is interested in "[brining] out the details from the viewpoint of the participants" (Tellis, 1997, p. 1) and to study the complexity within a specific, bounded case. This is true for the research which is described in this thesis. Nevertheless, I acknowledge that there are multiple strategies for doing qualitative PER but have made the limitation to focus on single case studies for this thesis (see Robertson, McKagan, & Scherr, 2018, for a discussion about the use of case-oriented research in PER). The limitations and issues of trustworthiness and ethics connected to this methodology will be discussed in Section 4.3.

Particularly, I position myself within a naturalistic approach to inquiry as described by Lincoln and Guba (1985). This approach to inquiry applies well with research in social sciences, such as education research. Naturalistic inquiry is a response to the scientific (or rationalistic) inquiry approach used in the "hard sciences". Guba and Lincoln (1982) defines the naturalistic inquiry in relation to the otherwise frequently used scientific approach, by describing each approach to inquiry in terms of different axioms. Three of these axioms are related to the 'nature of reality', 'inquirer-object relationship', and 'nature of truth statement'. I will here briefly describe these axioms and how my particular research fit these axioms. The first axiom states that within the naturalistic approach to inquiry there can be multiple realities that corresponds to a single, or multiple participants. According to Guba and Lincoln, these realities will most probably diverge from each other, making it unlikely to be able to form any kind of prediction between cases. My research fits this axiom well since it deals with students' experiences of physics phenomenon, and thus I interpret my participants as having their own lived reality. The second axiom deals with the relationship between inquirer and object of inquiry. In the type of research presented in this thesis, this relationship is likely to be influenced by either the inquirer or the participant. This is particularly true when working with human beings as I am doing in my research (see also Section 4.3.1). Within naturalistic inquiry, the third axiom, concerning the nature of truth statements, indicates that these truth statements are bound to the context of the inquiry which is true for my research. The aim of this inquiry is to form an idiographic body of knowledge, made up by individual or unique statements, that focuses on the differences in these statements. Because of this, as I will discuss further in Section 4.3.1, a researcher with a naturalistic approach to inquiry can only make 'fuzzy generalizations' (Bassey, 2001) of the research.

Having given this short introduction to qualitative research and naturalistic inquiry, I will continue this chapter by providing an overview of the methodological choices that I have adopted for the studies presented in this thesis. I will begin by describing the methodological choices that I have done regarding the data collection and the data analysis. The choices made for both data collection and analysis will be described individually for each paper. At the end of this chapter I will explain the ethical considerations and choices that I have done in my work.

4.1 Data collection

In this section I will give an overview of how the data sets have been planned and collected. It should be noted that although the first data set was collected as part of my bachelor's project (M. Eriksson, 2014) it was both planned and carried out by me. I have made use of both written answers to a questionnaire, audio-recordings and video-with-audio recordings for my different data sets. I will explain my rationale for using this type of data for each data set in this section. The second data set (Paper II) was collected by me in the first few months of me starting my PhD studies. The students that were chosen to take part in this data collection were first year university physics bachelor students. For the analysis in Paper I and II, I took a leading role in the analysis but worked closely together with my supervisors.

4.1.1 The first data set

From the data and the results obtained from M. Eriksson (2014), I believed that there was more to extract from the data by extending the analysis. This led me to further analysis and more results, which is presented in this thesis and in Paper I. In the following I describe the full data collection process.

The study associated with the first data set focused on students' conceptions of algebraic signs (+ and –) used in one-dimensional kinematics problem solving. In particular, I was interested in the ways in which students used these signs to describe both scalar and vector concepts, such as distance, speed, velocity and acceleration.

There were two student groups that took part in this data set; (1) physics students at the natural science preparatory program (*basåret*[23]) at Uppsala University, Sweden; and, (2) pre-service science teachers at the University of KwaZulu-Natal, South Africa. Although the two groups of students came from two different educational settings and had a large difference in number of years at the university, they were still believed to be similar in level of physics knowledge[24]. This data set consisted of two different parts; first, a written open-ended questionnaire was distributed to the students, and second, follow up interviews that were conducted with selected students. The data collection in this data set was planned by me together with my supervisor at the time, Cedric Linder. I performed the Swedish data collection (distribution of questionnaire and interviews) while the South African data was collected by Nadaraj Govender with whom I collaborated with during this project.

Questionnaire

The first part of this data set was collected through a written open-ended questionnaire distributed to students in the Physics 2 course at *basåret* and to third year pre-service science teacher students (see Figure 5 and Figure 6 below for the problem descriptions of the two problems at the questionnaire, and Appendix C for the full questionnaire used). The questionnaire had been tested and revised through several pilot-studies before the final version was implemented (for details, see M. Eriksson, 2014). The Swedish students were given the questionnaire in their native language (Swedish) while the South African students, who were of different ethnicities and had different native languages, were given the questionnaire in English.

[23] *Basåret* in Sweden is a program for students who have completed a secondary-school education but without necessary courses in the STEM subjects to be accepted to a university science or engineering program. The physics courses in Swedish upper-secondary education is similar to the A-level courses in the US and UK, or introductory level physics for non-science major students at university.

[24] The level of the Physics 2 course for Swedish upper-secondary school, the course taken by the Swedish students at the time of data collection, is seen to be almost equivalent to introductory level algebra-based physics at university.

The questionnaire consisted of two main problems with several questions for each of them. The students were asked to explain, as well as they could, their thoughts and the reason for using any algebraic signs (+ and –) that they used in their answers. It was very important for us that the questionnaire was as easy as possible for the students to complete, i.e. any ambiguous meanings should be excluded. Since we would not be able to obtain any clarifying information from most students (apart from the students who were chosen to take part in the interviews, see the next section), we also had to make sure that the students' answers would be clear for us, thus making each question as clear as possible.

In total 84 students (60 Swedish and 24 South African) participated through answering the questionnaire.

Problem 1: The motion of a rolling ball

A small ball rolls along a smooth surface (ignore friction). When the ball has rolled 2m, it reverses when it hits a barrier (no energy is lost during the collision) and it rolls back to its original position. For the questions below, please **explain** your reasoning carefully.

Figure 5. The problem description to the first of two problems given in the questionnaire. After this introduction, the students were asked to describe the motion, displacement, distance, speed, velocity and acceleration of the ball before and after the turn. For each question they were asked to explain the meaning of any signs (+ or –) that they used in their explanation.

Problem 2: Velocity and acceleration of a car chase

Imagine the following sequence:

(1) A police car is standing by the side of the road at the intersection between Dag Hammarskjölds väg and Kungsängsleden when she sees a Volvo travelling at a constant speed through a red light.

(2) The police car immediately starts chasing the Volvo, along a straight part of the road, accelerating from rest until reaching a maximum chasing speed.

(3) The officer holds this speed until she is alongside to the Volvo.

(4) She turns on the blue light signalling to the Volvo to pull over. The driver of the Volvo starts to slow down, the police car also slows down, staying alongside the Volvo.

(5) Both cars finally stop by the side of the road.

Figure 6. The problem setting for the second problem. 'Dag Hammarskjölds väg' and 'Kungsängsleden' are two main roads in the immediate area neighboring the university building where the Swedish data collection took place. Hence, these students could be expected to be familiar with these streets. The students were asked to describe the velocity and the acceleration of the police car during each step of this car chase using signs and/or arrows and explaining any signs that they used.

Interviews

The second part of this data set consisted of data from semi-structured follow-up interviews (Kvale, 1996) with purposefully selected (Patton, 1990) students among the answered questionnaires. Semi-structure interviews means that "the [interview] guide will include an outline of topics to be covered, with suggested questions" (Kvale & Brinkmann, 2009, p. 130) which was the case for my interview guide. By 'purposefully selected' I mean, following (Patton, 1990, p. 169), samples "from which one can learn a great deal about issues of central importance to the purpose of the research". In my case this involved students with questionnaire answers that was seen to be able to provide interesting insights into their use of algebraic signs. These interviews took approximately 15 minutes and were audio recorded with permission from each participating student. All interview audio files were subsequently transcribed verbatim by me. Each student was presented with their individually answered questionnaire in a stimulated-recall type of interview (Lyle, 2003). This 'stimulated recall procedure' is "an introspection procedure in which […] passages of behaviour are replayed to individuals to stimulate recall of their concurrent cognitive activity" (Lyle, 2003, p. 861). Through this process I was thus able to probe certain interesting answers or to seek clarification.

The interview guide used during the interviews consisted of three types of pre-determined clarifying questions; "(1) 'what sign would you use to describe displacement/speed/velocity/acceleration?', (2) 'how does the sign for velocity/acceleration change during the car chase?', (3) 'what does the sign for velocity/acceleration mean to you in everyday life/physics etc.?'." (M. Eriksson, 2014, p. 10). The first group of questions was associated with the first problem of the questionnaire, and the second group with the second problem. The third group of questions sought to provide understanding of the student's understanding of these signs in different context. Additionally, follow-up questions, seeking to clarify or deepen my understanding of the student's answers, were also present.

In total 11 students took part in these follow-up interviews—5 Swedish and 6 South African.

4.1.2 The second data set

The second data set was collected specifically for my PhD project and was used for Paper II. This data collection was initiated by my supervisors, but planned and carried out by me, in collaboration with my supervisors. The particular context of this set of data was circular motion tutorial type problem solving sessions in introductory physics.

My interest was to study the students' communicative practices used in their discussions.

For this data set, I chose to study first year physics bachelor students and decided to collect this data during one of the students' mandatory problem-solving sessions. I and some of my colleagues and supervisors had been present during several of the students' course sessions before the data collection was carried out, because I wanted to make the students used to our presence and to make them feel that I was a friend of theirs instead that of an outsider. During the data collection the students were working in small groups of 2-4 students in each group. I chose to make video-with-audio recordings of the student's discussions for this data set (for a discussion around the use of video data in qualitative research, see, for example, LeBaron, Jarzabkowski, Pratt, and Fetzer, 2018). Using video data allowed me to capture not only students' persistent representations, but also non-persistent representations such as gestures[25]. The videos were recorded using small cameras in two different positions (Figure 7) and a fellow PhD student provided technical support during all of these recordings. In addition, small devices for capturing audio was placed on the tables to ensure that all audio was being captured by either the video-with-audio-camera or the audio-recorder.

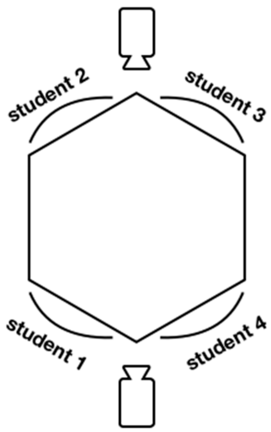


Figure 7. The data collection set up that was used for the second data set. Each group was recorded by two cameras at two different angles.

[25] It is argued that using video data allows researchers to obtain a deeper understanding of teaching and learning strategies, for example, through analyzing gestures (see Congdon, Novack, and Goldin-Meadow, 2016).

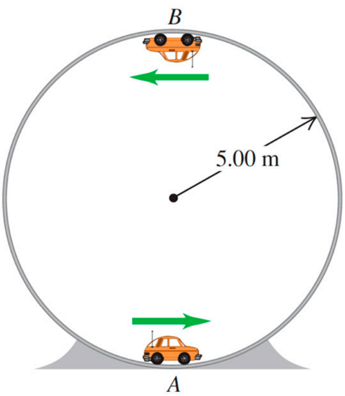
The data that was used for this project was collected during two different tutorial type recitation sessions with problems regarding uniform circular motion (for possible solutions to the given problems, see Appendix D[26]). The students were free to form their own groups, without intervention from the researchers, since we wanted to increase the possibility for them being grouped with people that they felt comfortable to collaborate with. All students were kept in the same classroom and could thus both visit and be visited by other students in other groups. The students in these problem-solving sessions were working with two different types of circular motion problems, one with a vertical circular motion, and the other with a horizontal motion. During each session we were able to collect data from two groups of students (in total four groups video-recorded).

The students who participated in this data set were of different nationalities and thus kept all communication in English. This was beneficial for us since all members of the research team then were able to understand the original videos. They had all signed ethical agreements prior to this data collection and thus agreeing to be video recorded for the purposes of the study.

In the first session the students were working with a problem regarding a uniform vertical circular motion. The students were asked to find "the magnitude of the normal force that acts on the car at point A and point B" for a remote-controlled car that was driving with constant speed on the inside of a vertical hollow cylinder (Figure 8). This problem was selected from the course textbook (Young & Freedman, 2016) and was included in the teacher's suggested list of problems that the students should work on and it matched our purposes very well.

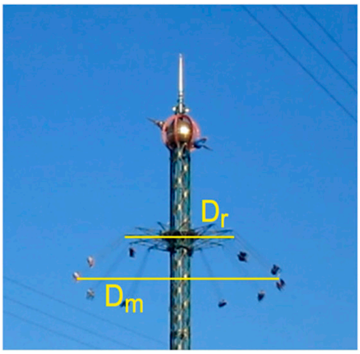
The second session consisted of two groups of students working on a problem regarding uniform circular motion in the horizontal plane. For this session we chose to use a problem that regarded a circular swing ride found at many amusement parks (see Figure 9). The students were, amongst all, asked to find the "forces [that] act on a rider with mass *m*" and to draw a free body diagram. This problem was suggested by us without any connection to the list of problems in the textbook.

[26] The solutions given in Appendix D are possible solutions to the problems given to the students during the second data set. The aim of the appendix is not to discuss common erroneous student strategies to the problems since this is provided elsewhere (Pendrill, 2020), but instead to provide a description of possible solutions.



"A small remote-controlled car with mass 1.60 kg moves at a constant speed of v=12.0 m/s in a track formed by a vertical circle inside a hollow metal cylinder that has a radius of 5.00 m […]. What is the magnitude of the normal force exerted on the car by the walls of the cylinder at (a) point A (bottom of the track) and (b) point B (top of the track)?"

Figure 8. The given problem (exercise 5.45) for the first session and the accompanying figure (Fig. E5.45) (Young & Freedman, 2016, p. 187). Figure and text is reprinted by permission of Pearson Education Inc., New York, New York.



"This photo shows the Himmelskibet ("Star flyer") ride visible from Copenhagen Hovedbanegård. The diameter at rest is 14 m and the chain length is 8 m. From the photo, the ratio between the diameters at motion and at rest can be estimated to 1.9.

1. What is the angle between the chains and the vertical?
2. If the ride makes a full turn in 6.3 s, what is the speed of the rider in the swing?
3. What is the acceleration of the rider?
4. What forces act on a rider with mass m? Draw a free-body diagram.
5. How could you use the photo to estimate the acceleration? Compare the value to your result in 3."

Figure 9. The given problem for the second session. Figure reproduced from Pendrill (2016, p. 4) (reproduced under CC-BY 3.0 license).

4.2 General analytic approach

I have used different types of analysis methods for different data sets. In this section I aim to describe the different types of analysis methods that I have used to give the reader an overview.

For the first data set I made a relevance structure categorization based on existing phenomenographic categories (for a description of the phenomenographic approach see Section 3.2). These phenomenographic categories are based on a naturalistic inquiry approach—an analysis of students' experiences. This data was partly collected as audio recordings and partly as written questionnaire answers. Through this method, the data that was collected for data set I was only around the students' spoken and written language, i.e. using only one semiotic system. During the interviews, the students had the possibility to use pen and paper to make drawings, another semiotic system, which could be used in order to enable my understanding of their thoughts in a better way, however this very seldom occurred.

To be able to gain further understanding of the students' experiences and how they communicate their disciplinary knowledge—the *communicative practices* used—for the second data set, I chose to include video as my way of collecting data. This allowed me to include more of the semiotic resources used by students when communicating amongst each other.

In this section I will describe the analytic approach I have taken. I will divide the section in two parts since my analysis is grounded in two similar but different approaches; the first part is a naturalistic approach (Section 4.2.1) and the second is multimodal transcriptions (Section 4.2.2). I will describe these analysis processes in general terms here, and later (Chapter 5) explain how I applied these analytic approaches to my own empirical data.

4.2.1 Naturalistic qualitative categorization

The first approach that I want to describe in more detail, to make the reader able to follow my analysis and results of my own data, is based on the naturalistic qualitative method known as a *phenomenographic analysis approach*. As described earlier in this thesis (Section 3.2), phenomenography seeks to understand peoples' experiences of a certain phenomenon. In phenomenography, the researcher seeks the qualitatively different ways people experience a certain phenomenon. In this type of analysis, the researcher takes on a second-order perspective, meaning that they present the ways other people experience the world around them, not how the researcher experiences the world, or what is right or wrong.

The phenomenographic categorization takes a naturalistic approach to analysis (Lincoln & Guba, 1985). This means that the researcher is interested in the ways in which nature is described by humans (their lived reality). However, it does not, in comparison to a rationalistic approach, seek to predict a single observed reality, because of the naturalistic belief of a multiple reality as experienced by different individuals.

As described in Section 3.2, the result of a phenomenographic analysis is an outcome space of categories of description which have an inherent hierarchy that ranges from the least advanced way of experiencing the phenomenon, to the most advanced way. This type of categorization, based on the kind of *hermeneutic* (e.g., Butler, 1998; Seebohm, 2004; Stiles, 1993) and constant comparative approach (Glaser & Strauss, 1967, see also Section 3.2) that are currently being drawn on for educational interpretive studies (e.g., Case, Marshall, & Linder, 2010; U. Eriksson et al., 2014b; Nielsen, 2012), is the result of an iterative analysis process where the researcher tries to understand the meaning of the descriptions that people give to a particular phenomenon. This iterative categorization process consists of several steps and ends when all emerging categories have been 'saturated' (Lincoln & Guba, 1985, p. 350). Lincoln and Guba (1985), drawing on the work of Glaser and Strauss (1967), exemplifies this process where the initial step is for the researcher to get a feel for the whole data set, by reading through the obtained answers. Starting with a subset of the data, the answers are then coded, and similarly coded answers will make up the emergence of categories of description. Throughout the emergence of these categories, the coded 'parts'—i.e. the categories—are constantly compared to the 'whole' data set. When the categories have emerged, the rest of the data is sorted into these categories, checking and re-checking the interpretation of the 'parts' as the categorization goes along. This iterative, comparative, cyclical process continues until saturation is reached, that is, when new answers sorted into the categories with have minimal effect on the interpretation of the meaning of the category and no new categories emerged. When the categorization has been finished, the categories are describing the properties of the content in each category. However, in this process it is important to acknowledge the researchers as part of analysis; the analysis and the result depend on the experiences and knowledge of the researcher. Hence, the analysis presented in this thesis reflects and depends on my background as a physicist and physics education researcher and the results would likely be different should the researcher be outside the physics discipline; only a physicist with my background could do a similar analysis as I have done and come up with the same results. This is an important, but often left out, characteristic of a naturalistic analysis approach.

4.2.2 Multimodal transcriptions

As mentioned earlier, the work presented in this thesis seeks to capture and analyse students' communicative practices when learning introductory physics. Parts of the data that make up the papers on which this thesis is based on, therefore uses dynamic video recordings (LeBaron et al., 2018). To capture all communicative practices that students' made use of, and for me to be able to analyse in detail, I chose to make multimodal transcriptions (Baldry & Thibault, 2006; Jewitt et al., 2016) of the video recordings. By making multimodal transcriptions the researcher makes a transduction (Section 3.1.3) from video data into written text and visual snap shots that also includes information about other semiotic recourses used by the students (Bezemer & Mavers, 2011). In this way I was able to combine the spoken language, with other non-persistent representations (e.g. gestures) and persistent representations (e.g. diagrams, written language and mathematical equations). Note that when making the transduction from video to a persistent multimodal transcription, the researcher is highlighting the content that is of most relevance to them. Bezemer and Mavers (2011, p. 195) notes that a thing "which is not considered central can be backgrounded, and features not deemed relevant to the analysis can be excluded." This can, for example, include drawings, body postures and gaze included in the video, but which are not relevant to the problem at hand as judged by the researcher.

An example of the transcripts that I was using when analysing the second data set (Paper II) can be seen in Figure 10. For each transcript I made use of **bold** lettering to refer to spoken emphasis and underlining to indicate that there were accompanying gestures and/or other formulations. These are represented [*italicized in brackets*]. It was important to me to include visual images in combination to the multimodal transcription to be able to analyse students' additional non-spoken resources, such as diagrams, mathematics, and, in particular, gestures. In these visual images I chose to add small solid arrows to more clearly show what I want the reader to focus on and dashed arrows to show a movement in some direction.

With this section, I have tried to give the reader a 'thick description' (Geertz, 1973) of the method I have been using for data collection and data analysis. It has been my aim to provide the reader with enough information to be able to follow the entire process of my research and to make my findings trustworthy. I will discuss the trustworthiness and ethical considerations of the work in this licentiate thesis in the next section.

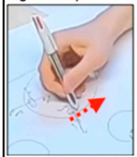
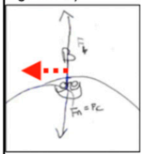
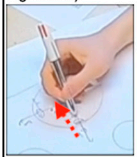
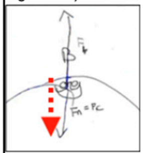
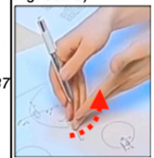
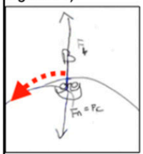
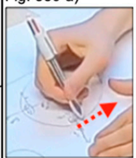
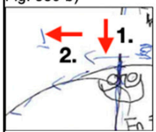
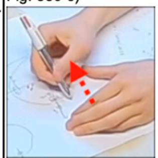
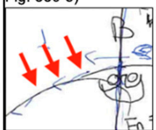
		Multimodal transcription in different semiotic systems		
Line	**Student**	**Spoken language**	**Gestures**	**Diagrams and sketches**
336	Delia	But how does it stay up? [*looks at the teacher*]		
337	Carl	[Answering for the teacher] Because, the velocity is going this way [*moves pen along velocity tangentially on top of the diagram, Fig. 337 a) and b)*],	Fig. 337 a) 	Fig. 337 b) 
		and the force is going this way [*gestures the direction of the force downward towards the centre of rotation, Fig. 337 c) and d)*]	Fig. 337 c) 	Fig. 337 d) 
		which makes the velocity vector change. [*puts hands together with the fingers continuously changing direction as he aligns them along the changing displacement that makes up the circular path, Fig. 337 e) and f)*]	Fig. 337 e) 	Fig. 337 f) 
338	Delia	Yeah? [*incredulous questioning to Carl and teacher*]		
339	Carl	[Attempting to have the dimension of variation that he opened become more discernable to Delia and the rest of the group] But it [*the car*] stays up because it's going like this [*draws velocity vector arrow tangential to the loop, Fig. 339 a) and b) nr. 1*],	Fig. 339 a) 	Fig. 339 b) 
		but the force goes like this [*draws force arrow directed downward, Fig. 339 c) and b) nr. 2)*],	Fig. 339 c) 	
		which makes it change like this- changes like this, and so on [*draws how the velocity vector changes, Fig. 339 d) and e)*]. It changes- the vector changes, but not-	Fig. 339 d) 	Fig. 339 e) 
340	Delia	Oh, okay. I see.		

Figure 10. Example of the multimodal transcription used in the analysis of the second data set. The columns show (from left to right) line number, student (pseudonym) and used semiotic systems (spoken language, gestures and sketches).

4.3 Trustworthiness and ethical considerations

All research within education is in one way or another dealing with human beings. Thus, it is important that the researcher ensures that the current ethical considerations are followed[27], and most importantly that the participants' privacy is adhered to. In this section, I will begin by evaluating my study in terms of trustworthiness issues of qualitative research. I will then describe the ethical considerations I have made concerning my research—the data collection and analysis—and shortly describe how I related my data towards the current data protection regulations (GDPR, Section 4.3.2). It is important to note, however, that the presence of ethical guidelines in research is not enough to make sure research are conducted ethically, but each researcher needs to make ethical decisions themselves (see Johnsson, Eriksson, Helgesson, and Hansson, 2014).

4.3.1 Trustworthiness

In all types of research, the trustworthiness of the researcher and the research approach is a central factor. This links to the quality of the research and can be related to issues around the *truth value*, *applicability*, *consistency* and *neutrality* of the research (see Table 3).

In research fields within physics (and other natural sciences), researchers often take a rationalistic (scientific) approach to research. However, the research I identify with instead uses a naturalistic approach, as described earlier in this chapter. Guba (1981) and Guba and Lincoln (1982) sets up their view of differences between these approaches in terms of approaches taken to ensure the trustworthiness of the research. The relationship between these approaches to inquiry in terms of these aspects of trustworthiness are shown in Table 3.

Table 3. The different aspects of trustworthiness used in scientific (rationalistic) and naturalistic inquiry. From Guba (1981).

ASPECT	RATIONALISTIC/ SCIENTIFIC TERM	NATURALISTIC TERM
Truth value	Internal validity	Credibility
Applicability	External validity/ Generalizability	Transferability
Consistency	Reliability	Dependability
Neutrality	Objectivity	Confirmability

I will here describe my own considerations towards these aspects of trustworthiness and the choices I made in my own research and analysis. For each of the four aspects I will

[27] In Sweden, researchers are referred to the ethical guidelines as described by the Swedish Research Council (2017)

begin by describing how Guba & Lincoln (1982) has proposed this aspect and then describe how I have related my work to each of these.

Credibility

> "How can one establish confidence in the "truth" of the findings of a particular inquiry for the respondents with which and the context in which the inquiry was carried out?" (Guba and Lincoln, 1982, p. 246)

Credibility, or testing the truth value, is about the researcher showing that the analysis and results are believable. This aspect is also about having both the researcher and the objects of research making sense of the research. To test this aspect, Guba (1981) suggests certain methods that can be applied to increase the credibility of the research. Such methods include looking at the data from different perspectives and having colleagues and peers debrief the data. Regarding the research for this thesis, I was constantly making sure to discuss the results and analysis with my supervisors and other colleagues. In this way I have been able to get input from other perspectives, hence increasing the credibility of my results.

Transferability

> "How can one determine the degree to which the findings of a particular inquiry may have applicability in other contexts or with other respondents?" (Guba and Lincoln, 1982, p. 246)

The aspect of finding the applicability of a study, to what degree the research will be applicable to other contexts and participants, is suggested to be referred to as the research's transferability. Within the scientific inquiry tradition this is called to test the generalization of the research. Stake and Trumbull (1982) proposed to use the term *naturalistic generalization*, which means that the researcher makes sure that he or she is giving enough information to the reader to decide for themselves, based on their own personal previous experience, how transferable the results are. Bassey (2001) instead proposes the term *fuzzy generalizations*, a generalization of which "x in y circumstances may result in z"[28]. He states that in this case it is up to the reader to find out in what conditions this statement may be true.

To help make the decision about the generalization, i.e. transferability, of a research, a provided *thick description* of the research is proposed (Geertz, 1973). In this thesis I

[28] Two other forms of generalizations proposed by Bassey (2001, p. 10) are *scientific generalizations*, which states that "if x happens in y circumstances then z will occur in all cases", and *probabilistic generalizations* on the form "if x happens in y circumstances then z will occur in about p % of cases".

have tried my best to provide such thick description by openly provide detailed descriptions about the data collection and analysis. It is my hope that the readers of this thesis will be able to, together with their previous experience, make judgements for themselves about the generalizability of this research.

Dependability

> "How can one determine whether the findings of an inquiry would be consistently repeated if the inquiry were replicated with the same (or similar) respondents in the same (or a similar) context?" (Guba and Lincoln, 1982, p. 246)

This aspect, the research's *dependability*, is linked to the question about consistency, and is the naturalistic equivalence to the rationalistic term *reliability*. This is related to how well the research can be replicated if the research is repeated in the same, or similar, context. In the context of my research, working with human beings, the exact replication of a study is never fully possible. Nonetheless, the researcher still needs to give a detailed description about the inquiry, to make it possible to reproduce. To increase the dependability of the research in this thesis, I have provided a detailed description of the research process, including data collection and analysis, to ensure that the methods used could be reproduced.

Confirmability

> "How can one establish the degree to which the findings of an inquiry are a function solely of respondents and of the conditions of the inquiry and not of the biases, motivations, interests, perspectives, and so on, of the inquirer?" (Guba and Lincoln, 1982, p. 246)

The *confirmability* of the research, the naturalistic answer to the question of *neutrality*, and the equivalence to the rationalistic term *objectivity*, is about how well the study and results are shaped by the participants, instead of the inquirer. This means that the responsibility should be removed from the researcher and instead placed on the data (Guba & Lincoln, 1982, p. 247). To establish this criterion, I have provided a clear path along each step of the research, to show how each step fit together and make it possible to follow each step of the research process as well as to show how the process is independent from me as the researcher. However, as I have pointed out already (Section 4.2.1), my own experiences as a person and researcher will inevitable influence the interpretation of the data, and consequently the analysis and results of my research.

4.3.2 Ethics

For both my data sets I have carefully planned and conducted the data collection to maintain my participants' anonymity and safeguard their interests. This included making sure all participants were, to the best of my ability, informed about the goal and aims of the study, as well what the data they provided in the study was going to be used for. To follow all ethical considerations, I carefully constructed information sheets and obtained written informed consent from all my participants. Below I will describe the process of obtaining informed consent for my studies.

For the first data set the students were informed that by responding to the questionnaire they were actively taking part in the data collection, providing me with informed consent for the study. The same information sheet, also functioning as informed consent, attached to the questionnaire that was given to the students can be found in Appendix A[29]. Students who were interested in participating in an additional audio-recorded follow-up interview voluntarily provided their e-mail address to this information sheet before handing it in. It is worth noticing that by not collecting any other information to this stage, such as name, gender, personal identification number and so on, the students provided information that were in no way able to be traced back to them. On the information sheet the students were all given information about the study, how the data they provided were going to be used, and for what purposes. The Swedish students were given this information both orally by me and written in the information sheet, both of them in Swedish. The South African students were all given the information in English on the information sheet. They were all also encouraged to e-mail any questions or concerns that they had to me personally.

For the second data set, before starting any data collection, I distributed an informed consent sheet to the students (see Appendix B). At the same time, I gave all students the same information verbally as well. All students who were being recorded during this data collection had handed in the informed consent form. On this form we specifically informed the students that data might be collected through "audio, video, or [from] written surveys". The students were also informed that the data that was collected would come to be used in scientific publications such as journal articles and conference presentations. The consent form particularly stated that the reporting of the results in these ways could include "video/audio excerpts and quotations from [their] answers [which they] provided". Further, although not explicitly stated on the consent form, I emphasized orally and made clear during

[29] The information sheet given in this appendix is the English version which was distributed to the South African students. The Swedish students were, however, given the information sheet and questionnaire all in Swedish.

each stage of the data collection that each student who was taking part in the data collection understood that their participation was voluntary, and that they at any point could withdraw their consent to participate.

The data that I have been collecting and processing during my research reported in this thesis include both 'non-personal data' (such as, written questionnaire answers and audio recordings) and what is to be regarded as 'personal data' (i.e. data that can be used to identify a single individual). This personal data is, for example, students' name, e-mail address, and, face and body posture identified from the video recordings. However, none of the data I have been processing is considered to be 'sensitive data'[30]. Since my data didn't contain any sensitive data, the risks for taking part in the projects could be considered to be minimal.

During the processing of the data I, and my colleagues, took great caution to make sure we were handling the data in a rightful way, to protect the individual student's integrity, following national and international regulations (for example, as discussed by the Swedish Research Council (2017) or as described in terms of the GDPR, see below). One of the ways in which this was done was through informing the students about the project both orally and written, and to clarify what data was going to be processed, what their participation consisted of, and their right to decline participation and to withdraw their consent.

All digital data such as video recordings from the second data set are stored on portable hard drives in locked rooms at Lund University. The hard drives are accessible by me and my supervisors. The non-digital data, such as students' questionnaire answers or signed consent forms, are stored in locked rooms within the research groups at either Lund and/or Uppsala University.

To maintain the students' anonymity and integrity, when presented in articles or presentations, the students have been given pseudonyms. When appropriate, anonymization is also adhered to when using images of the students' hand-gestures instead of using their whole body or their face.

GDPR

In May 2018, the General Data Protection Regulation (GDPR, European Parliament, 2016) was implemented as the required data protection regulation for all companies and organisations within the European Union directed to regulate the handling and processing of personal data.

The data that are used in the projects in this thesis have all been collected before the GDPR was implemented. The processing of data prior to GDPR may thus deviate from

[30] 'Sensitive data' is considered, for example, ethnicity, religious and political beliefs, trade union membership, sexual orientation, and biometric data.

the way I should be processing the data as of GDPR. Nonetheless, I am trying as best as I can to keep myself updated about the regulations, and follow regulations for processing data today, and collecting data in the future.

5 Analysis

In the preceding chapters I have tried to explain to the reader where I position myself and my research and describe the theoretical stance that underpin the work presented in this thesis. In this chapter I aim to further describe the analysis that I have made of the data sets that make up the Papers I and II. I will for each of the papers describe the data that was used, the analysis that was made and the results from the analysis. In the next chapter (Chapter 6) I will give a synthesis of the findings that the papers are based upon and also discuss these findings in terms of the research questions as introduced in Chapter 1.

5.1 Paper I

The first paper in this thesis focuses on, as introduced in Section 4.1.1, the understanding and use of algebraic signs in one-dimensional kinematics problem solving. In the data set which make up this paper, the participating students were introductory level physics students in two different educational settings, and I studied how these students make sense of and apply ('read' and 'use') plus (+) and minus (–) signs when solving one-dimensional kinematics problems. It has been proposed in several studies that students have multiple understandings of when to be using plus and minus signs when solving physics problems (Brahmia, 2018; M. Eriksson, 2014; Govender, 2007), and that the application of coordinate systems pose challenges to students (Rebmann & Viennot, 1994; Viennot, 2001).

Grounding my study in these previous findings, I turned my interest towards a deeper knowledge of students' understanding and use of these algebraic signs and how this could be understood in terms of their *relevance structure* (see Section 3.2.1). To the best of my knowledge, no studies have looked at students' relevance structure in this way in physics education, and I turned my interest towards using this way of understanding the aspects of algebraic signs in vector kinematics in terms of these concepts. This new way of analysing the results took the departure in a theoretical framework of variation theory (see Section 3.2.1) that was found to be an interesting way of understanding the results. With this way of looking at the data, the aim for the research presented in Paper I was to contribute to the collective research results on students' learning challenges involving algebraic signs in introductory level kinematics. I suggest that for all disciplinary knowledge, students need to get to learn how to "read" the disciplinary representations in order for them to discern the DRAs which are represented and use them appropriately. This "reading" points to a person's relevance structure and can be explained by what they find relevant—what they focus on—for a given context. Such reading of a given situation is directly related to the ways in which the particular DRAs gets used by the students.

In this section I will begin by introducing the data and results on which this analysis was based on. I will thereafter describe the analysis I made for Paper I and finally describe and discuss the results in more detail.

5.1.1 Description of data

As I described in the section above, the data that was used for this paper came from the first data set which was used in a previous bachelor's thesis (M. Eriksson, 2014). In this work I made use of already existing 'categories of description' (see Section 3.2) obtained and described by Govender (1999, 2007) for my analysis and was able to sort the data into these categories using the naturalistic qualitative and iterative analysis process described in Section 4.2.1. The obtained outcome space, from M. Eriksson (2014), made up by a set of collective-level categories of description[31] of the use of algebraic signs in one-dimensional vector kinematics, is reproduced in Table 4.

Table 4. The obtained categories of description from Eriksson (2014). Note that Category B, which was part of Govender's (1999) originally obtained outcome space, was not identified in this data set and is thus not represented in this table.

CATEGORY	DESCRIPTION
A	Algebraic signs are not applied in vector-kinematics
C	Algebraic signs are applied as changing magnitude
D	Algebraic signs are applied as both magnitude and direction
E	Algebraic signs are applied as directions

In Paper I, I used these collective-level categories but shifted my focus towards the individual level of how students find algebraic signs relevant for them, i.e. how these signs are *read* and *used* in the given context.

[31] Note that the 'collective-level' points to "identifying the [actual] ways in which something may be experienced" (Marton & Booth, 1997, p. 136).

5.1.2 Categories of relevance structure

Through the re-analysis of the data and the obtained categories from M. Eriksson (2014) I was able to extend the analysis and subsequently identify four categories of relevance structure (Table 5) representing individual-level categories.

The relevance structure analysis was done by re-analysing the existing data in terms of students' relevance structure (Marton & Booth, 1997)—what they find relevant for a specific task. In this process, I focused in the individual level, making the categories represent relevance structure on the individual level. This analysis followed a naturalistic inquiry to research (see Lincoln & Guba, 1985, and Chapter 4).

Table 5. Identified categories of relevance structure. Table reproduced from Paper I. Note that the category numbering does not represent the category numbering in Table 4 above.

CATEGORY OF RELEVANCE STRUCTURE:	"READING" – VARIATION DESCRIBED IN:	"USE" – FOCUS OF INTENTION (RELEVANCE STRUCTURE PERCEIVED):
A	No specific assignment of signs	Nothing necessarily specific in kinematics terms
B	+ and – assignment (single purpose)	Representing changing magnitude
C	+ and – assignment (dual purpose)	Representing magnitude in the case of acceleration Representing direction in the case of velocity
D	+ and – assignment (dual purpose)	Representing direction by convention Representing direction by choice

The distinct interpretation of each of these categories will be described in the following subsections. For each category I will give an overall description of the meaning of this way of "reading" and "use" of the algebraic signs. I will then give some descriptive excerpts that represent this category. For each of these excerpts I will use Q and I to refer to questionnaire or interview, respectively, and the letter S to refer to student's answer from both sources.

Notice that the description of each category, along with the student examples, are reproduced verbatim from Paper I. I have highlighted this by decreasing the right margin slightly.

Category A: Algebraic signs do not necessarily have specific relevance in kinematics

Students that experience this relevance structure do not consider algebraic signs to be needed specifically in kinematics. This is because directional signs can be replaced by directly referring to the given direction linguistically. For example:

Q:	Explain the speed and velocity of the ball before and after it turns. Explain the meaning of any algebraic signs (+ and –) that you use.
S:	*[…] I think that + and – seems a bit unnecessary. Why don't [we] just say a motion to the right or left?*

I:	Would [the velocity] have any signs in this case?
S:	*No, not when we have decided forward as left. I don't really think in terms of plus and minus, but I think in terms of right and left.*

Excerpts that have been sorted into this category show that students are reluctant to use signs to specify displacement, velocity and/or acceleration in one dimension, or they don't find any motivation for using these signs.

Category B: When an algebraic sign is assigned to a kinematic unit it is seen as being relevant for representing a changing magnitude

Students that experience this relevance structure appear to be connecting their way of reading algebraic signs in everyday life in relation to getting bigger or smaller. For example:

I:	What do you think that the signs for velocity show?
S:	*Plus to me means that it is going faster, that the velocity increases. And minus should then be the opposite, that the velocity simply decreases.*

S:	*I experience plus as something that is getting bigger and minus as something that is getting smaller.*

This category of relevance structure illustrates how students can get to experience signs as having a single purpose of indicating changing magnitude, often connecting the sign for acceleration to an increase or decrease of velocity and vice versa.

I:	What does the signs for acceleration mean to you?
S:	*Increase or decrease of velocity.*

I:	So when [the car] goes from some velocity to no velocity [what does it mean to you]?
S:	*Then it is deceleration, I'm thinking negative acceleration.*

From the above excerpts we see that students find signs to be used to describe a change in magnitude. However, this change in magnitude is, similar to Category A, not directly linked to a given coordinate-system.

Category C: The assignment of algebraic signs in kinematics has dual relevance: for representing changing magnitudes in the case of acceleration, and for representing direction in the case of velocity

Students that experience this relevance structure see algebraic signs as having a dual purpose in kinematics. In the case of velocity, they indicate direction, and in the case of acceleration they indicate magnitudes.

S:	*[I]n velocity the signs only specify the direction of motion, however in acceleration it means speeding [up] or slowing [down].*

S:	*[W]hen it comes to velocity + and – only show direction. When it comes to acceleration they only show the acceleration's increase or decrease and don't take direction into consideration. Why it turned out this way I don't know!*

This relevance structure category can be described to show how students find algebraic signs to have different meaning, or usefulness, for different aspects such as velocity and acceleration. Students find that algebraic signs should be used, but that the signs have a dual purpose for use; magnitude or direction.

Category D: The assignment of algebraic signs in kinematics has dual relevance: for representing direction by convention, and for representing direction by choice

This category of relevance structure illustrates how students can get to experience signs as being functional for indicating how direction gets to be assigned; by convention or by choice. Direction by convention is often stated explicitly, as illustrated in the following examples:

Q:	Is the direction important to be able to decide the motion of the ball? Explain.
S:	*[…] The motion is positive, if the direction of the ball is to the right [as] in this case.*

Q:	Is there any difference to the motion of the ball before and after the turn? Explain the meaning of any algebraic signs (+ or –) that you used, if any.
S:	*The motion is negative (–) after [the turn]. Because its motion is in the opposite direction.*

Similarly, representing direction by choice is illustrated in the following transcript excerpts:

I:	And what do the signs mean to you in physics?
S:	*It is the direction, partly. Or the direction in relation to how you decide on it.*

Q:	Is there any difference to the motion of the ball before and after the turn? Explain the meaning of any algebraic signs (+ or –) that you used, if any.
S:	*No difference except that directions are opposite. If we choose the initial direction as positive (+) then the other direction after the ball hit the barrier would be negative (–).*

This final category of relevance structure shows that students find algebraic signs to have dual purpose, but both with connection to direction; either direction by convention or direction by choice. However, this direction is often linked to the direction of motion, and not necessarily to the direction of a vector.

The implications of these categories of relevance structure will be further discussed in Chapter 6.

5.2 Paper II

The goal for Paper II was to study the analytical combination of social semiotics and variation theory in the case of small group tutorials. This combination has been previously suggested as a possible fruitful strategy for analysis (C. Linder, 2012) but has yet not been practically tested. The particular context chosen for this was introductory level circular motion. It has been shown in previous studies (e.g. Pendrill, Eriksson, Eriksson, Svensson, and Ouattara, 2019) that students struggle with the conceptual understanding of the physics behind circular motion. Thus, this context was suggested to be rich in terms of data.

As described in Section 4.1.2, this data was made up of video recordings of groups of students taking part in a tutorial type recitation session. During these data collections I was interested in the communicative practises that the students used. I will in this subsection start by describing how we made the selection of the data (Section 5.2.1), describe the data set in more detail by looking more closely into the two chosen episodes (Section 5.2.2), and then describe the analysis process used (Section 5.2.3).

5.2.1 Selection of data

During the data collection phase, I video recorded two groups each during two different tutorial sessions and thus had to select what parts of the data I should choose to analyse. In order to do this selection, I first watched the videos from all four groups. Since I had been present during all group recordings, I had an overall impression of the group dynamics which made this selection easier. I first began by watching all videos in full to be able to form my own view of the data. Thereafter I selected rich data that I was interested in analysing further. This selection was based on the observable communication made between the students in the group and the present learning possibilities. I selected data from one group from each of the two sessions that was recorded. The selection of the episodes was discussed with my supervisors and we reached consensus on the chosen episodes. I will hereafter, following the terminology from Paper II, refer to the two different group sessions as two different *episodes*.

The selected data was chosen because of the rich communicative sequences in the data, i.e. sequences of the data where the students were communicating with several different semiotic systems and where I could see that they were doing progress in the collective learning and understanding of the problem. The data episodes that were not selected for further studying were not seen to be as rich in 'inter-student communication' and lacked internal teaching and learning opportunities.

5.2.2 Description of the data

For the purpose of the second paper, the theoretical perspective that I chose to take was with focus on the communication between students that represented sequences of learning within the group. These sequences were characterized by the presence of student created 'transductions' between different semiotic systems (see Section 3.1.3). When the selected sequences had been identified I did a full verbatim transcription of the episodes. For the multimodal transcriptions shown in this subsection, each student has been given a pseudonym to maintain their anonymity. The main semiotic system presented in the transcripts in Table 6-Table 9 below is spoken language, which has been combined with references to other semiotic systems used by the students—mainly gestures, sketches and mathematics. These other systems are referred to in the verbal transcript in *italics* (see also Section 4.2.2 for a detailed description of the multimodal transcriptions used in this data set). In the transcripts below I chose to show these semiotic systems as different columns. However, since the communication between the students in the sequences showed here, involved talk, gestures and sketches, rather than mathematics, I chose not to add a separate column for mathematics.

In the following subsections I will give a description of the selected sequences of the data for the two chosen problems which were presented in Section 4.1.2. First, I will describe the data corresponding to the first problem regarding a vertical circular motion, and thereafter describe the data relating to the problem with a horizontal circular motion. The descriptions of the data given here are in parts reproduced almost verbatim from Paper II.

Episode 1: The car problem—vertical circular motion

The students in this episode—throughout Paper II pseudonymized as Alex, Becky, Carl and Delia—spend a large portion of time discussing what forces were acting on the car when at the top of the circular loop. This is also the particular sequence which I decided to focus my analysis to. This sequence involved a lot of communication within the group, particularly between Carl and Delia. In the middle of this discussion, one of the teachers who were present during this activity approached the group and briefly participated in the discussion. The teacher's participation was focused on approaching a statement given by Carl and did not necessarily give the rest of the students a full explanation to the situation.

From the very beginning of the group addressing this tutorial problem, Alex showed the most confidence for how to proceed to solve the problem numerically. The first person to really challenge his explanatory understanding was Becky who was not convinced by Alex' explanation regarding what forces were acting on the car at points A and B. In an effort to reach a more compelling conceptualization of what these forces were, Becky drew a large diagram (Figure 11) of the car and the cylinder and marked the forces that she felt were acting on the car at points A and B. This diagram was then used by the rest of the group for the rest of the emerging discussion. The thread of this emerging discussion started with strong disagreements about what forces were acting on the car. At this point they concluded that there should be three forces; normal force, gravitational force, and centripetal force. However, they quickly entered into a lack-of-agreement phase regarding the direction of the centripetal force at the given points and where it originated from.

The sequence that I focused on to analyse in more detail lasted just over a minute and started after Delia proposed that there should be a force acting on the car directed upwards at the top of the loop aiming to keep the car from falling straight down. This statement was followed by another statement from Carl, proposing that this suggested upward force doesn't exist (i.e. doesn't act on the car) which resulted in the conversation seen in Table 6.

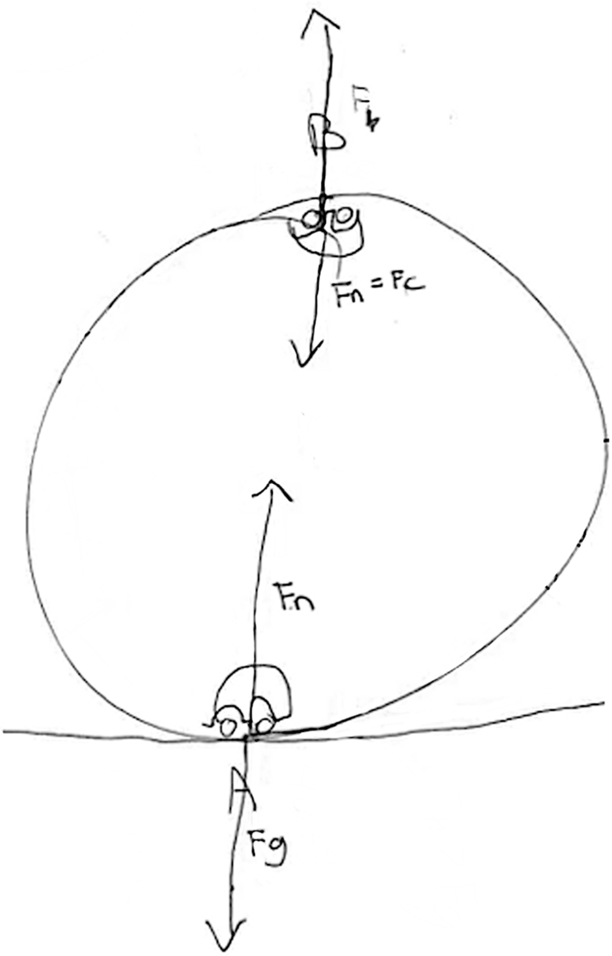
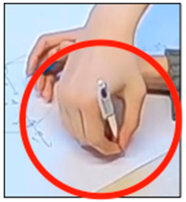
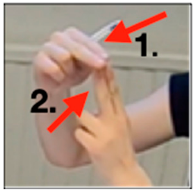
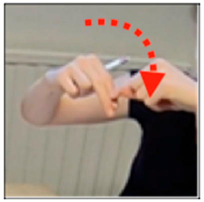
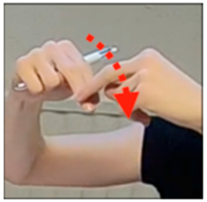
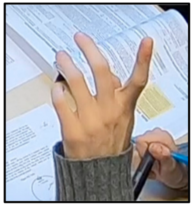
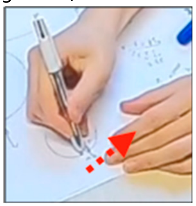
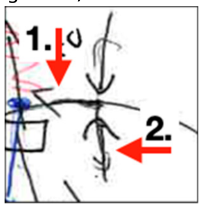


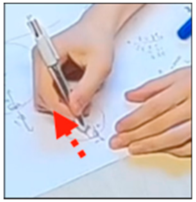
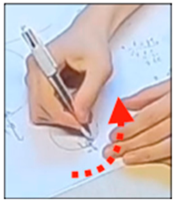
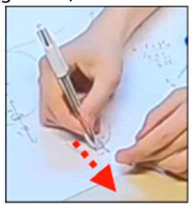
Figure 11. The diagram that Becky drew which the group then centered most of their discussion around.

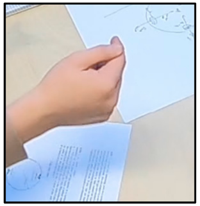
Table 6. Verbatim multimodal excerpt from the first discussion between Carl and Delia. This conversation started after Delia proposed that there should be a force on the car directed straight upwards to keep it from falling down. Carl countered Delia's statement proposing that the upward force doesn't exist.

		Multimodal transcription in different semiotic systems			**The observed relevance structure (as enacted)**	
Line	**Student**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that get introduced**
307	Carl	I don't think this force [*the centrifugal force that the students had drawn on a common sketch of the problem situation, Fig. 307 a)*] exists. [*scratches out the upward outward force sketched in acting on the car at point B from one of the used diagrams, Fig. 307 b)*]	Fig. 307 b) 	Fig. 307 a) 	The force that the track exerts on the car to get it to follow a circular path	Real and fictitious forces acting on the car
308	Alex	No, it does.			The force that the track exerts on the car to get it to follow a circular path	None
309	Becky	It does.			Experienced outward-acting forces in circular motion	None
310	Carl	It doesn't, but let me- *[interrupted by Delia]*			The force that the track exerts on the car to get it to follow a circular path	None
311a	Delia	But **how would it stay up** otherwise? [*looking at Carl challengingly*]			Sum of forces equals zero, for a static situation	The direction of the normal force acting on the car
311b	Alex and Becky	[*looks at Delia and chuckles insecurely when she asks the question*]				

312	Carl	**Oh, because** the velocity is this way, [*puts right-hand fingers horizontally in the air, Fig. 312 a) nr.1*], but the acceleration this way [*adds left-hand fingers vertically upwards to the other hand, Fig. 312 a) nr.2*], and as the force exerts [*puts left-hand fingers vertically downwards to the right hand, Fig. 312 b)*], the velocity changes like this. [*moves right and left hand simultaneously to represent the car going downwards in the circle, Fig. 312 c)*] So, there is no force going like this. [*moves pen upwards, Fig. 312 d)*]	Fig. 312 a)  Fig. 312 b)  Fig. 312 c)  Fig. 312 d) 		Direction of the velocity vector, acceleration vector and force vectors for an object in circular motion.	Changing of the different vectors.

		Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
Line	**Student**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that get introduced**
		But the force acts like this- [*puts right and left hand finger together similar to Fig. 312 b) and c), Fig. 312 e)*]	Fig. 312 e) 			
313	Delia	But **something** has to keep it up? [*uses index finger to point up*]			Treating the car as being in a static situation at top of the circular track	The direction of the normal force acting on the car
314	Carl	**No, no**-			N/A	N/A
315	Alex	Ahh! [*indicating that he is starting to construct a new understanding*]			N/A	N/A
316	Carl	The velocity is going like this [*draws velocity vector horizontally, Fig. 316 a) and b) nr. 1*],	Fig. 316 a) 	Fig. 316 b) 	Changing velocity and force that car exerts on the car and these are responsible for the circular motion	Changing direction of velocity

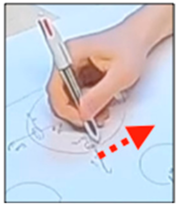
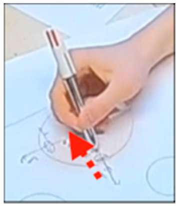
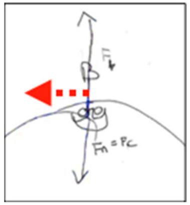
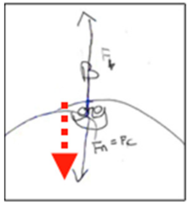
		Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
Line	**Student**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that get introduced**
		but then the force goes like this, [*draws force vertically downwards from the top, Fig. 316 b) nr.2 and c)*]	Fig. 316 c) 			
		which makes it change. [*gestures with pen the circular path, Fig. 316 d)*]	Fig. 316 d) 			
317	Delia	But- [*Interrupted by Carl from going back to her question of what would stop the car from falling down*]			What would happen to a static car in this position?	The direction of the normal force acting on the car
318	Carl	But there is no force [acting on the car] going like this [outwards]. [*uses pen to gesture force vertically upwards on top of diagram, Fig. 318 a) and b)*]	Fig. 318 a) 	Fig. 318 b) 	Normal force acting on the track is not a force acting on the car	Forces acting on the car in terms of what is real and what is fictional

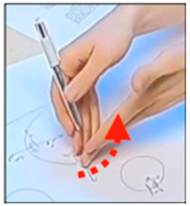
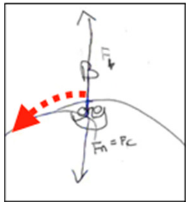
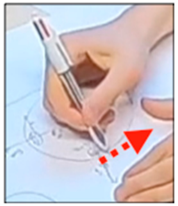
		Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
Line	**Student**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that get introduced**
319	Alex	It's the other way. [*uses index finger to gesture the direction of the force*]			Car pushes on track outwards and in return the track pushes on the car inwards	Newton III pairs of forces.

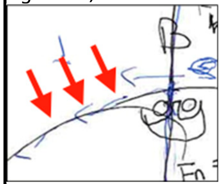
In the section of the discussion shown in Table 6, Carl opened up the possibility that the suggested upward force acting on the car at point B did not exist (implying that it is a fictious force, line 307). At this stage in the conversation, neither Becky, Delia nor Alex, agreed with him based upon the assumption that the car needed a force to prevent it from falling straight down ("something has to keep it up", see lines 311 and 313). However, Alex was starting to show signs of giving serious thought to Carls explanation following his opening up of new dimensions of variation by, for example, varying the direction of the velocity (see line 312), i.e. starting to incorporate these new DRAs into his relevance structure. The DoVs that Carl opened up were underpinned by a shifting from a static thinking stance to a dynamic thinking stance vis-à-vis an inertial reference frame point of view. Carl did this by drawing on the gesture semiotic system to use different gestures in his explanation (see the gesture column under lines 312 and 316). This was characterized as a "gesture-based unpacking" of the physics relationships that Carl saw between the changing velocity of the car, the corresponding acceleration, and the specifying of a force (from the wall exerted on the car) responsible for that acceleration. To do this, Carl generated variation within the DRAs, thus opening up the corresponding dimensions of variation. These DRAs corresponds to the students' main identified critical DRAs for solving the given problem.

Right after the discussion shown in Table 6, one of the teachers who were present during this activity approached the group and, after being asked, confirmed Carl's idea about the non-existent upward force acting on the car at the problem-given point B. Both the teacher and Carl clarified what they meant by the "force doesn't exist" by stating that the upward force does not act <u>on the car</u> at point B. Delia, who was still not convinced once again asked how the car could stay up otherwise, see Table 7.

Table 7. Verbatim multimodal excerpt from the second discussion between Carl and Delia. In this excerpt, Delia again asks about how the car can be able to stay up and is given yet another explanation from Carl.

		Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
Line	**Student**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that get introduced**
336	Delia	But how does it stay up? [*looks at the teacher*]			What would happen to a static car in this position?	The direction of the normal force acting on the car
337	Carl	[Answering for the teacher] Because, the velocity is going **this way** [*moves pen along velocity tangentially on top of the diagram, Fig. 337 a)*] and b), and the force is going this way [*gestures the direction of the force downward towards the centre of rotation, Fig. 337 c) and d)*]	Fig. 337 a)  Fig. 337 c) 	Fig. 337 b)  Fig. 337 d) 	Velocity vector and how it changes and how the force that the track exerts on the car is responsible for the continuous changing in velocity	Variation of the direction of velocity and simultaneously of the force that the wall exerts on the car.

		Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
Line	**Student**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that get introduced**
		which makes the **velocity** **<u>vector change</u>**. [*puts hands together with the fingers continuously changing direction as he aligns them along the changing displacement that makes up the circular path, Fig. 337 e) and f)*]	Fig. 337 e) 	Fig. 337 f) 		
338	Delia	Yeah? [*incredulous questioning to Carl and teacher*]			N/A	N/A
339	Carl	[Attempting to have the dimension of variation that he opened become more discernable to Delia and the rest of the group] But it [*the car*] stays up because it's going like <u>this</u> [*draws velocity vector arrow tangential to the loop, Fig. 339 a) and b) nr. 1*], but the <u>force</u> <u>goes like</u> **this** [*draws force arrow directed downward, Fig. 339 c) and b) nr. 2)*],	Fig. 339 a)  Fig. 339 c) 	Fig. 339 b) 	Velocity vector and how it changes and how the force that the track exerts on the car is responsible for the continuous changing in velocity	Variation of the direction of velocity vector as a function of the movement of the car in a circle

		Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
Line	**Student**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that get introduced**
		which makes it change like this- changes like this, and so on [*draws how the velocity vector changes, Fig. 339 d) and e)*]. It changes- the vector changes, but not-	Fig. 339 d) 	Fig. 339 e) 		
340	Delia	Oh, okay. I see.				

In the piece of the discussion shown in Table 7, Delia and Carl continued to debate the upward force. Carl (lines 337 and 339) once again tried to demonstrate to Delia how the velocity, acceleration and force were related with respect to having the car follow a circular path. Carl did this by opening up a DoV based on the direction of the relevant velocity vector. He did this by using gestures and sketches as illustrated in Table 7. Even though, finally, in line 340 Delia seemed to indicate that this DRA was now in her focal awareness, a further look at the video data suggests that her response in line 340 is to be seen to be in alignment with the teacher, and thus this aspect remained 'transcended' to her.

Summary of Episode 1

In Episode 1 the students can be seen to be struggling to find a common relevance structure that includes a common perception of what forces acting on the car are relevant for correctly solving the tutorial problem (in this Episode, at point B at the top of the circular loop). Delia was arguing for an upward force to keep the car from falling inwards, which was initially supported by Alex and Becky. At the same time Carl opened up dimensions of variation to help Delia get to see how the velocity, acceleration and force from the wall acting on the car at this point were related, and in so doing wanting her to see why there was no such upward force that is relevant for correctly solving the problem—in his words, it does not "exist". To be able to share this part of his relevance structure, Carl used gestures (in addition to the diagram and spoken language) to open up these dimensions of variation.

In this episode Carl generated three different, but interconnected, dimensions of variation, namely the direction of the velocity, acceleration, and the force from the wall acting on the car. From the discussion that made up the Episode it is suggested that Delia was not able to see how the changing velocity of the car was related to specifying the forces acting on the car as she seemed not to connect these DRAs simultaneously. As stated above, I propose that the velocity was transcended to her.

Episode 2: The swing problem—horizontal circular motion

The second episode that was analysed also consisted of four students (Eric, Frank, Gloria and Holly—pseudonyms) who were trying to find out what forces were acting on a person in a circular swing. In the particular section of the data where I focused my analysis the students are struggling to find a common agreed understanding about whether there should be a force on the person directed outwards from the centre of the circle. The person that initiates the discussion is Gloria who suggests that there should be in total four forces acting in the person in the swing to keep the swing from falling into the centre of the circle. This section lasts about 1,5 minutes and although the students are keeping up a good discussion, they leave the problem with the forces without having reached an agreed understanding.

In the start of this particular sequence, Gloria and Eric have agreed that there should be three forces acting on the person; a tension force, gravitational force and a force stemming from the acceleration. However, Gloria quickly introduced the idea that there should also be a fourth force acting on the rider, in the opposite direction to what she referred to as the "acceleration force", F_a (Figure 12). She drew a free body diagram of the rider, being to the left in a horizontal circle, which included this outward force on her own piece of paper and introduced it to the other students (Figure 12). At this point Frank suggested that this outward force was a "fake" force. This claim initiated a new thread of discussion in the group which is given in Table 8.

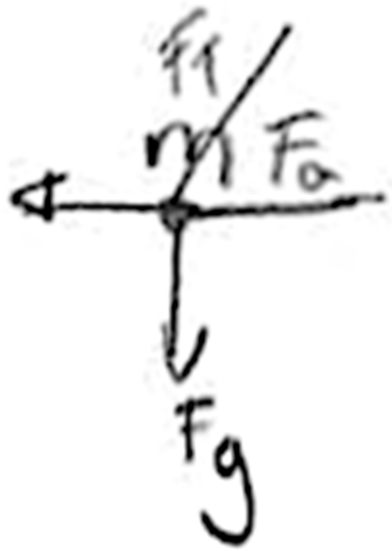
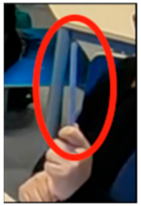
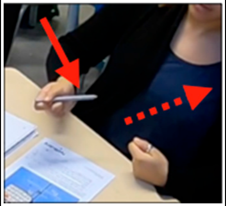
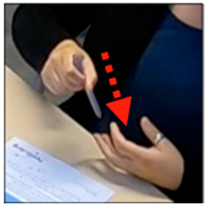
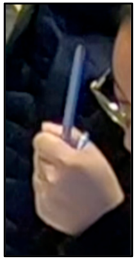
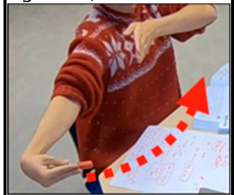
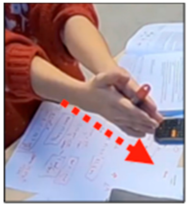


Figure 12. Gloria's free body diagram made at the time of discussion that began on line 179 in Table 8.

Table 8. Verbatim multimodal excerpt from the first discussion between Frank and Gloria. This sequence starts after Gloria describes what forces she thinks acts on the person in the swing, and that there needs to be an additional force keeping the swing from falling into the centre of the circle.

		Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
Line	**Student**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that get introduced**
179	Gloria	At the moment the tension force is holding it, [*places pen vertically upwards, Fig. 179 a)*] the acceleration is pulling it inwards, [*places pen horizontally and moves body as being "pulled inwards", Fig. 179 b)*] and your gravitational force is pulling you down, so you don't fly up. [*moves pen vertically downwards, Fig. 179 c)*] But what stops you from getting, like, **pushed in**?	Fig. 179 a)  Fig. 179 b)  Fig. 179 c) 		Non-intertial frame of reference, tension force, centripetal acceleration, gravitational force	No variation but rather identification of forces
180	Frank	Pushed in? [*looks at Gloria*]			N/A	N/A

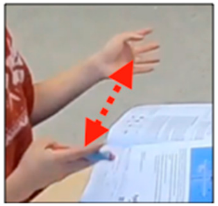
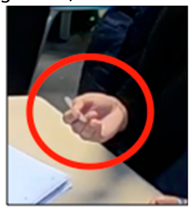
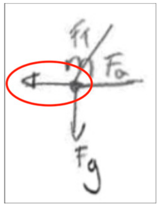
		Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
Line	**Student**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that get introduced**
181	Gloria	Yeah […] You have the tension force which is holding [it]- [*places pen vertically upwards*]			Tension force	Direction of the tension force
182	Frank	No, **your velocity** is [*places right hand vertically "forward", Fig. 182 a)*] keeping you from going [*puts hands together, Fig. 182 b)*] inside.	Fig. 182 a)  Fig. 182 b) 		Velocity vector	Direction of velocity vector
183	Gloria	Yeah. [*looks at Frank*]			N/A	N/A

		Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
Line	**Student**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that get introduced**
184	Frank	And the **rope**, what it's doing is like, keeping you in a circle. [*makes a right angle with his right hand and arm and moves in a semi-circular path, Fig. 184 a)*]	Fig. 184 a) 		Tension force in the rope and non-existing centripetal force	Direction of tension force in the rope. Non-existing centripetal force to illustrate that it's missing
		But there is no force going- pushing you inside. [*gestures with right hand how you are being "pushed inside", Fig. 184 b)*]	Fig. 184 b) 			
185	Gloria	But how are you then not **sucked in**? [*looks at Frank*]			Centripetal force	N/A
186	Frank	Because your velocity is always tangential. [*puts both hands together and moves them horizontally forward*]			Tangential velocity vector	Direction of velocity vector
187	Gloria	Yeah, yeah-			N/A	N/A

In the sequence presented in Table 8, Gloria was using different movements and gestures to show the other students her idea of what the force situation looked like. Frank was strongly opposed to this idea and argued that the velocity of the swing was keeping you from being drawn to the centre of the circle. This didn't convince Gloria from arguing that there needed to be a force preventing the swing from being "sucked in" (line 185). To try to convince Gloria, Frank introduced additional gestures to try to get her to discern the velocity of the swing and rider and, for example, positioned his hand and arm in a right angle to show the relationship between the velocity and the tension of the rope to gesture-out how the rope should be seen to be "keeping you in a circle" (line 184).

Towards the end of this part of the discussion (see Table 9) Holly re-introduced the idea that an outward force was needed to counter the inward pulling tension force of the swing chord. Frank immediately challenged this by declaring it "not even a force" just a consequence of Newton's third law. But Holly's proposal was authoritatively supported by Gloria who established her authority from what she "learned in school" before she declared that an outward force is needed to prevent the swing from getting "sucked in".

Table 9. Verbatim multimodal excerpt from the second discussion between Frank and Gloria. Frank, who has not succeeded in convincing Gloria that the outward force does not exist explains that this outward force is a fictitious force.

		Multimodal transcription in different semiotic systems			**The observed relevance structure (as enacted)**	
Line	**Student**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that get introduced**
205	Holly	**It is** always another force. [*looks at Frank*]			Non-inertial frame of reference, centrifugal force	N/A
206	Frank	It's not even **a force**. It's just created because of the third **Newton's law**. For every force there is a [unclear] force in opposite direction. [*move hands back and forth*]			Non-inertial frame of reference	Variation of direction of forces in general (N3 law)
207	Gloria	So, okay so for me- because I **learned it in school**, you draw the other side too. [*points pen in direction of "other side", Fig. 207 a) and b)*] And that just makes sense because otherwise that looks as you are- yeah, you **get sucked** in. But because I am not allowed to draw a velocity force at the moment-	Fig. 207 a) 	Fig. 207 b) 	All forces, and in particular a fictitious force outwards (centrufugal)	Variation in the direction of centric forces
208	Eric	Okay-			N/A	N/A

		Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
Line	**Student**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that get introduced**
209	Frank	Because you- if you don't draw the tangential velocity. [*draws a pictorial arrow, Fig. 209 a) and Fig. 209 b), to represent the tangential velocity seen from Frank's perspective*] You have to draw like this, [*draws pictorial arrow at right angle to the arrow in Fig. 209 b), Fig. 209 c)*] **centrifugal** force. [*makes quotations marks in the air, Fig. 209 d)*]	Fig. 209 a)  Fig. 209 d) 	Fig. 209 b)  Fig. 209 c) 	Velocity vector and centrifugal force	Variation of centric force outwards (fictitious)

In the excerpt presented in Table 9 Frank went on to again try to get Gloria to appreciate the changing direction of the velocity of the swing as it moved in a circle. However, Gloria remained centrifugally adamant (line 207). Frank tried to appease the group by suggesting that they needed to conceptually take the tangential velocity into account, and if they did not, they would be forced to incorrectly include a centrifugal outward force into their deliberations.

Summary of Episode 2

In the excerpts from Episode 2 shown above, the discussion revolved around the need for an outward force acting on the person on the swing. This force was proposed to be necessary to prevent the swing from being drawn to the centre of the circle. On the other hand, Frank was convinced that no such force exists, and neither was needed when taking into consideration the forces that give rise to the circular motion. Also, even though he drew attention to some relevant physics using elaborate sets of gestures, the intuition of his peers did not allow that consideration to be incorporated into the group's relevance structure.

The students in this episode focused on a combination between two different DRAs; the direction of the velocity and the tension force. Frank focused on the velocity and how the velocity was changing direction during the swing ride, while Gloria didn't seem to discern the velocity—I suggest the velocity was transcended to her—but rather focused on the fictitious outward force. When generating variation to the direction of the velocity, Frank opened up this DoV for Gloria and the other students.

From the description of the data episodes given here, my next subsection will include a more detailed description of the analysis process of the data.

5.2.3 Analysis of episodes

In this subsection I will describe the analysis process that I used for analysing the two Episodes described above. For the analysis I applied key theoretical elements from my chosen theoretical frameworks, social semiotics and variation theory (Chapter 3). I will describe the analysis process systematically to illustrate how the two frameworks can be used to fruitfully complement and supplement each other in qualitative analysis in ways that broaden and enhance existing understanding of the complexities involved in learning physics.

The analysis process comprised three steps: (1) with the use of social semiotics, identify rich communicative learning sequences within each group; (2) identify students' enacted relevance structure in these learning sequences; and (3) apply variation theory of learning to identify in what ways students experienced different

DRAs through the use of variation. I will for each of these steps use the data from the episodes to exemplify the process.

The primary intention of the full analysis was to describe the students' communication during a problem-solving group task, and pinpoint how, if possible, they were able to help each other forward to a better understanding.

Step 1: Identification of rich communicative sequences

The analysis that I performed began by using the theoretical framework of social semiotics. The use of this framework in the analysis of this data set facilitated the identification of important threads of the students' communication to be able to understand what was happening in the students' discussion (Tables 6-9). For this step of the analysis I made use of multimodal transcriptions of the students' conversations, which were analysed first individually and then collectively by myself and my supervisors in order to achieve trustworthiness of the study (see also Section 4.3.1). In these threads I looked at the way in which the students were communicating, providing me with more in-depth information about the communication, compared to looking at only what they were communicating.[32]

The interesting threads that made up the basis for this analysis were identified through the focus on the communication between the students. I analysed the data with the focus on trying to understand what was discussed using different semiotic systems—the semiotic systems that were used by the students were spoken language, gestures, sketches, and mathematics—and identified sequences that could be seen as parts that brought the discussion forward for better understanding among all students in the group, referred to in Paper II as *learning sequences*. In these learning sequences, presented in Table 6-Table 9, I could see that the students were spending time discussing certain DRAs for solving the specified problem. The most critical identified DRAs for the students in Episode 1, as mentioned before, included velocity, acceleration, and the force from the wall acting on the car. For the students in Episode 2, the most critical DRAs were the velocity and the tension force. The identification of these learning sequences was made possible by paying attention to all of the DRAs that the students were focusing on. However, since the DRAs of these problems are identified from the discipline's perspective, the aspects that students chose to consider may or may not overlap with these disciplinary aspects. The observed parts of the collective enacted relevance structure that matched DRAs consisted of the following

[32] The focus of the analysis presented in Paper II was on the analysis rather than on the physics concepts and knowledge by the students.

components: the system, radius, mass, normal force, gravitational force, centripetal force, acceleration and velocity.[33]

Step 2: Students' enacted relevance structure

The next step of my analysis was to try to understand what the communication could tell me, i.e. what did the students mean and intend to do in the chosen communication sequences? From the sequences identified during the first step of the analysis I could, for example, identify how Carl tried to get Delia to understand why the car doesn't fall down from the top of the loop (see Table 6 and Table 7), while Frank wanted Gloria to understand why there is no force pulling the swing outwards (Table 8 and Table **9**). To understand why Carl and Frank focused on these aspects I looked more closely into what the students showed to be focusing on and what they expressed to be important for the specific task. As discussed earlier (Section 3.2.1), a person's *relevance structure* is what a person finds to be relevant for solving a certain task and following Euler et al. (2020), I will refer to the student's *enacted relevance structure* when I talk about the relevance structure that was identified from the discussions. Thus, I examined the identified sequences with the aim of understanding what the students in these sequences were showing to be their enacted relevance structure.

In the discussion shown in Table 6 and Table 7 above, Delia could be seen to be constantly arguing that there needs to be something to keep the car in its track in the top part of the loop (Table 6, lines 311-313 and Table 7, line 336). In the way that she was communicating in this sequence, I interpret this such that her focal awareness was on the forces of the car as a static object, instead of dynamically. The velocity of the car was 'transcended' to her. I thus identified that her enacted relevance structure in this case was that there needed to be an additional force directed upwards, to make the forces of the static car balance out, which in turn keeps the car from falling down. On the other hand, Carl was able to focus on the changing velocity and the forces of the car simultaneously (Table 6, lines 312-316 and Table 7, lines 337-339) which I interpreted as his enacted relevance structure contained the relationship between the change in velocity and the force from the wall, hence indicating a dynamic view to the problem.

From the other set of the data (Table 8 and Table **9**), I was able to do the same type of analysis to identify the enacted relevance structure of Delia and Frank. In this episode, Gloria suggested that there should be a force directed outwards on the swing to prevent it from being "sucked in" (Table 9, line 207). I suggest that her enacted

[33] In Paper II, the term "components" was used because what emerged was a series of descriptions that were not always fully compatible in the sense that different students presented what could only be characterized as DRA subsets.

relevance structure did not include the tangential velocity of the swing—for example, she argued that she was "not allowed to draw a velocity force at the moment" (Table 9, line 207)—whereas Frank's enacted relevance structure appeared to contain the velocity as a DRA seen from his comments about the tangential velocity (Table 8, lines 182-186).

Looking at the discussion more closely like described above I argue that I was able to identify Carl, Delia, Frank and Gloria's enacted relevance structure and how their individual view differed in relation to the others'. I next sought to understand more about the effect of the communication, and I was able to identify how the students engaged in the arguments in the discussion with the intention to change their peers' relevance structure. For example, in Episode 1, Carl wanted Delia to pay attention to the connection between the change in velocity and the force from the wall— "Because, the velocity is this way, and the force is going this way which makes the velocity vector change" (Table 7, line 337). On the other hand, Frank, in Episode 2, wanted Gloria to see the connection between the change in velocity and the tension force of the chain— "No, your velocity is keeping you from going inside. [...] And the rope, what it's doing is like, keeping you in a circle" (Table 8, lines 182 and 184).

The above excerpts highlight what I identified as being attempts to change their peer's relevance structures. Time after time Carl tried to make Delia focus on the velocity as a DRA. This suggests that Carl was able to discern that Delia lacked a dynamic understanding of the problem and wanted to make her see it by using both speech and gestures. Similarly, Frank used the same approach when trying to convince Gloria on the importance of the tangential velocity. I interpret this as an example of Delia and Gloria not bringing together—i.e. coordinating—the critical DRAs in their relevance structures simultaneously. I will come back to this discussion in Section 6.2.

Step 3: Generating variation

After I identified the students' individual enacted relevance structures and noticing that the students could be seen to be intending to change their peers' relevance structure, the next step in my analysis was to understand more of how the students were doing this. What mechanisms and tools were they using to try to make this possible? This means that I looked more closely into the ways in which students' relevance structure diverged from their peers' and how they tried to make their relevance structures converge by offering variation around a certain important DRA of the problem, by introducing variation around this DRA. As mentioned earlier, I suggest that once a DRA is being varied, by experiencing different values of this DRA, it will be referred to as a DoV. The variation in this sense is known as offering different values to the DoV.

To gain this understanding I analysed the communication from a variation theory perspective while looking at the chosen sequences when they were trying to convince each other to change their relevance structure. Using this perspective, I was able to identify a structured, but spontaneous, variation in important aspects of the problem. Variation theory states that one needs to experience difference against a background of sameness to be able to discern a new aspect. One example of this can be seen in Episode 1 and show how Carl wanted Delia to focus on the velocity as a DoV and thus created variation around this—in this case how the direction of the velocity vector changed to give rise to a centripetal acceleration—using gestures, while at the same time keeping the relationship between the velocity and the force invariant. I found the DRA corresponding to the direction of the velocity vector and how it changed, to be particularly important in the students' discussions. This seemed to be the DRA that was the main divider between the students' different views to the problem. Both Carl (Table 6 and Table 7) and Frank (Table 8 and Table 9) brought up this DRA while trying to respond to Delia and Gloria's proposals regarding the force situation for the car and the swing, respectively. Further, they created a spontaneous, but intentional, variation within this DoV when presenting different values of this aspect. Additionally, this variation was created against a background of sameness—both Carl and Frank kept the relationship between the direction of the velocity and the direction of the acceleration and the force towards the centre of the circle invariant. However, from the analysis I could see that this variation in itself may not be enough for the other students to change their enacted relevance structure if they are not able to discern the particular DRAs. I will return to this issue in Chapter 6.

The last question that I asked myself during the analysis process was regarding how the students offered this variation to their peers. I could see that Carl used gestures (see Table 6, line 312, and Table 7, line 337) in addition to spoken language and diagrams. Similarly, for Episode 2, Frank also made use of additional gestures (see Table 8, lines 182-186) when trying to convey his message to Gloria. I was able to identify that the use of gestures offered different possibilities for discerning the critical aspects of the problem, compared to what the sketches, diagrams and spoken language alone could. In both cases, the changing direction of the velocity represented different values of the velocity DoV.

Summary of analysis of episodes

In this short subsection I would like to summarise the analysis process described in Section 5.2.3. With the analysis my aim was to, through a combination of social semiotics and variation theory, be able to describe the learning process within each group and find commonalities between the groups.

The first step included looking at the data with a social semiotic lens, trying to identify what DRAs that the students were focusing on during their discussions, and to identify what semiotic systems and resources that they used. By doing this I was able to identify what I referred to as 'learning sequences' which were identified to include attempts to bring the discussion forward and enhance the collective understanding. The semiotic systems that were most frequently used by the students in the discussions were spoken language, gestures, diagrams and sketches, and mathematics. As one might suspect, I also found that speech, as a single semiotic system, was not enough for communicating the physics between the different parties in the group discussion (cf. Airey & Linder, 2009).

The next step in the analysis included a closer look at what I refer to as the underlying meaning of the communication in the identified learning sequences. By looking at the data through trying to identify students' enacted relevance structure I was able to find two different approaches to the problem. Either the students considered the velocity (and change in velocity) to be important for solving the given problem or they didn't. A lengthier discussion around these different approaches is given in Section 6.2. I could also see that the students were trying to change each other's relevance structure through the identified communication. This identification of the two approaches and the understanding of how they tried to change each other's relevance structure was made possible through my consideration of the identified semiotic systems used and of the DRAs that I could see were being focused on, both of which had been identified in the first step of the analysis.

The last step in my analysis looked more closely into the structure of how the students were trying to help their peers to a new understanding of the problem. I did this by looking at the identified sequences from a variation theory perspective, from the point of view of the two identified approaches. This step of the analysis also took close consideration of the identified semiotic systems and semiotic resources that the students used, as identified in the first step of the analysis. By doing this third step of the analysis, I was able to identify that students were trying to change their peer's relevance structure by generating spontaneous but structured variation within identified critical DRAs for the problem. This identification was only possible by considering all semiotic systems that the students used, and not only their speech.

In this subsection I have given a description of the analysis process connected to the second data set. However, I have not yet offered any discussion around the results which are described here. Instead I aim to do so in Chapter 6 where I will also answer the research questions set up for this thesis.

6 Findings

In this chapter I will answer the research questions presented in Chapter 1. I will also discuss the findings from the analysis described in the previous chapter in relation to these research questions.

6.1 Research question 1

The RQ corresponding to Paper I was:

RQ1 *What are the individual level categories of variation of experiencing relevance structure with regard to algebraic signs (+ and –) in introductory kinematics problem solving in university physics education?*

In answering RQ1, I applied a relevance structure analysis to an existing set of collective level categories of students' conceptions of the use of algebraic signs in one-dimensional vector kinematics (Govender, 1999, 2007). By doing this analysis, I was able to identify four categories of relevance structure (Table 10) corresponding to individual level categories of how students 'read' and 'use' plus (+) and minus (–) signs for different concepts in this context. Each category represents qualitatively different ways that students read and consequently use these algebraic signs which suggests that students are focusing on different aspects of the use of algebraic signs for the same context.

The identification of these categories suggests that there are certain critical aspects, connected to the teaching and learning of the use of plus (+) and minus (–), that largely goes unnoticed by students, for example, the connection to a coordinate system. The results indicate that there is not enough appreciation in physics teaching and learning for the communicative practices that are connected to the use of algebraic signs. As a pertinent example, with direct link to the results from the first data set, students are not given enough support to understand the underlying, disciplinary meaning existing in the plus and minus signs—the direction in a chosen coordinate system. Thus, it is suggested that the directional meaning of these signs often are *appresent*[34] (C. Linder, 2013; Marton & Booth, 1997)—present but not directly visible—to students. As a result, there is no reason for using signs in this context as the signs do not provide any additional useful information for the students, who rarely make a direct link to the use and application of a defined coordinate system. One example of this is how students express their experience of algebraic signs in everyday-life and physics in the same way—directions are expressed in terms of 'right' and 'left', instead of 'plus' and 'minus'. Further, for some students, signs indicate a change in magnitude without any reference to a direction of motion in relation to a defined coordinate system. Perhaps not surprising, yet troublesome, is how this omitted reference to a coordinate system is present also when students do make the connection between plus and minus signs and directions. For example, one student explained that, in the first questionnaire problem, "the motion is positive, if the direction of the ball is to the right", without making a reference to a chosen coordinate system.

Table 10. The hierarchical structure of the individual-level categories of relevance struture also presented in Table 4.

CATEGORY OF RELEVANCE STRUCTURE:	"READING" – VARIATION DESCRIBED IN:	"USE" – FOCUS OF INTENTION (RELEVANCE STRUCTURE PERCEIVED):
A	No specific assignment of signs	Nothing necessarily specific in kinematics terms
B	+ and – assignment (single purpose)	Representing changing magnitude
C	+ and – assignment (dual purpose)	Representing magnitude in the case of acceleration Representing direction in the case of velocity
D	+ and – assignment (dual purpose)	Representing direction by convention Representing direction by choice

Based on my analysis, it is proposed that difficulties, such as the ones described above, stem from the unclear use of disciplinary semiotic resources in physics teaching, as connected to, for example, sign conventions and coordinate systems. The communicative practices used by teachers must include appropriate semiotic resources to help students discern the disciplinary relevant aspects that are relevant for the particular object of learning. Additionally, these resources need to have high

[34] The phenomena of something being 'appresent' "refers to the fact that although phenomena are, as a rule, only partially exposed to us, we do not experience the parts as themselves, but we experience the wholes of which the parts are parts. We do not experience silhouettes but phenomena (material or conceptual) in all their complexity of space and time." (Marton & Booth, 1997, p. 100).

pedagogical affordances (Airey & Eriksson, 2019) in order to maximize students' possibility to discern the DRAs. I suggest that teachers need to give more consideration to what semiotic resources will help students to discern the relevant DRAs and to discuss what constellation of resources that is critical for promoting this disciplinary discernment (cf. Airey & Linder, 2009). From my analysis I suggest that the affordance of algebraic signs is largely unnoticed by students. These signs, although just a 'small' detail of one or two short lines, could be said to have high disciplinary affordances (Airey & Eriksson, 2019), and at the same time students are expected to discern the disciplinary affordance that is appresent in the sign itself—a formidable task! The high disciplinary affordance of signs and the difficulty to applying them correctly is noted in other contexts in physics as well (see, for example, Brahmia, Olsho, Smith, and Boudreaux, 2020, and the references therein). For example, Newton's law of gravitation,

$$F = -G\frac{M_1 M_2}{r^2}, \qquad (1)$$

includes a minus sign with high disciplinary affordance, something that for most students largely goes unnoticed. The inherent meaning of this minus sign, signalling that the force is attractive, opposite, and equal in size on two bodies, is 'well hidden'. In each context, these, to students, subtle use of disciplinary information seems to be interpreted differently. Plus and minus signs seem to mean different things to students in different contexts, although they originate from the same thing—the connection to a chosen coordinate system (see Viennot, 1979). As a consequence, the challenges of using signs should not be underestimated.

In conclusion, it follows directly that it is crucial for teachers to be aware of the DRAs which algebraic signs are used to bring to focal awareness. As a result, teachers need to consider the appropriate semiotic resource(s) that could offer students to discern these DRAs (possibly in addition to signs), unpack that information (Fredlund, Linder, Airey, & Linder, 2014), and help students to make the appropriate disciplinary discernment (U. Eriksson, 2014). I suggest that only then will these DRAs become part of the students' relevant structures and increase the possibilities for learning.

6.2 Research question 2a

The first RQ corresponding to Paper II was:

RQ2 *In the context of students' learning in tutorial type group work:*

a) in what different ways could students' reasoning be characterized when trying to find the forces acting on an object in circular motion?

This RQ could be answered from an early analysis of the second data set. From applying a social semiotic lens to the data, I was able to identify in what ways students' reasoning could be characterized when trying to find the forces acting on an object in a vertical or horizontal circular motion problem. I was able to do so by looking for what DRAs the students were focusing on. In so doing, I was able to identify that the students applied two qualitatively different views to this problem, depending on whether they treated the object as momentarily at rest or not; I refer to them as a *static approach* and a *dynamic approach*, respectively (Figure 13). I suggest that these approaches are a direct consequence of the students' 'enacted relevance structure' (Euler et al., 2020). From the analysis presented in Section 5.2.3, I recognized that neither Delia, nor Gloria seemed to have discerned the velocity of the car or swing. At the same time, Carl and Frank was seen to enhance the possibilities for this DRA to be discerned by the other students by offering variation within this DRA—varying the direction of the velocity vector. Thus, I concluded that the discernment of this particular DRA—velocity of the object—could be seen as the divider between how the problem was approached, and consequently, the success in understanding the problem. Below I will describe each approach in more detail.

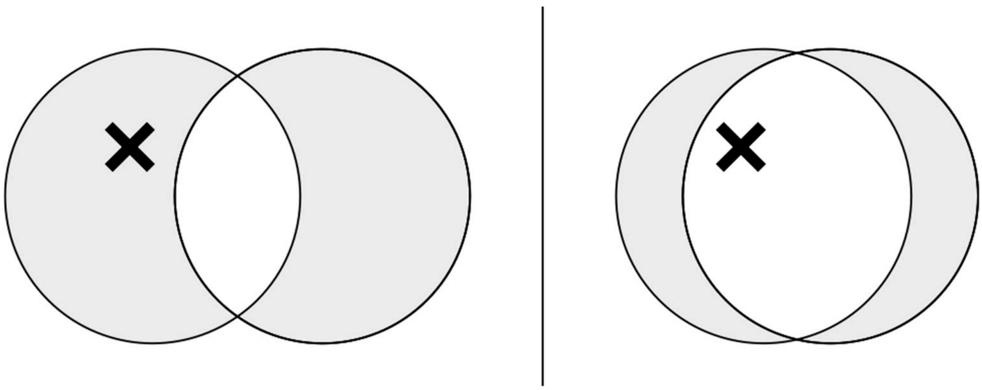


Figure 13. Two different Venn diagrams representing the two approaches to circular motion problems; a static approach (left) and a dynamic approach (right). The cross in each Venn diagram represents the particular DRA of the velocity of the object, the left circle represented the DRAs for the given prolem and the right circle shows the relevance structure. The white 'cut-outs' shows the overlap between student's relevance structure and the DRAs of the problem.

The first approach—*a static approach*—to identify the forces acting on an object in a circular motion suggests that students are looking at the problem statically. This means that they want to specify the forces acting on the object in circular motion by adding extra (inertial) forces, enabling them to apply the same relations as in statics, before they take any velocity, or change in velocity—i.e. acceleration—into consideration. Thus, I interpret this as that the students are seeing the object as stationary, which can also be seen as if the students are treating the object as stationary within an accelerating coordinate system. I suggest that this can be translated into having a relevance structure that does not include the velocity of the object—a critical DRA for any circular motion problem. This approach was seen with both Delia and Gloria in the second data set. When viewing the problem as static, it is suggested that students are finding Newton's first law (N1) to be a primary critical factor to consider in order to successfully solve the problem. I saw that students that could be seen to be focusing on N1considered any velocity of the object is seen as being momentarily zero (the object is at rest) and hence the forces acting on the object in all directions (here, both in x- and y-direction in a defined cartesian coordinate system) should add up to zero. Students' will to treat an object at the top of a vertical circle as momentarily at rest were also identified in Pendrill et al. (2019).

The second approach—*a dynamic approach*—to this problem was to look at it dynamically; this entailed that the students took velocity into consideration before they were to specify the forces acting on the object. In contrast to students with a static approach, they knew that N1 cannot be applied for an accelerating object. Unlike the static approach, students who held a dynamic approach to the problem identified the object as having a changing velocity—i.e. not at rest or in uniform motion—and hence succeeded in solving the problem. In terms of relevance structure, the dynamic approach means that the DRAs representing the velocity were, in fact, part of the students' individual relevance structure. This was seen with both Carl and Frank and I argue that this was decisive for them to be able to solve the problem correctly; any attempt to solve similar circular motion problems will only be successful if students take velocity into consideration, i.e. having a dynamic approach to solving those problems.

The static and dynamic approach could, of course, also be seen to be originating from viewing the problem from two different frames of reference; either an *inertial* or a *non-inertial frame of reference*. Students who are identified as having a dynamic approach to solving the problem, can be seen to be treating the problem from a non-accelerating reference frame—an inertial frame of reference—which leads them to a (correct) interpretation of the forces related to the centripetal acceleration. On the other hand, students who are identified as having a static approach can be interpreted as treating the problem from an accelerating reference frame—a non-inertial frame of reference—where the sum of the forces acting on a (in this system) non-accelerating object should add up to zero. They would then have to add a force directed radially outwards, corresponding to a ‘centrifugal force’ in this frame of reference. However, I see no evidence from the analysis of the data that neither Delia nor Gloria explicitly use or refer to inertial forces or accelerated reference frames for solving the problems, whereas Carl and Frank’s way of solving the problem could implicitly point to the use of an inertial frame of reference.

In conclusion, the static and dynamic approach was identified through the second step in the analysis model described in Section 5.2.3. This division into two different approaches suggests that students’ relevance structure is a major factor for how successful students are in solving the suggested problems. This also suggests that it is crucial that critical DRAs are brought to the fore in the students’ individual relevance structure in order for them to approach and solve the problem successfully. Should they fail to bring in all relevant DRAs into their relevance structure, the probability for them to successfully solve the problem will be substantially lower, if not zero.

6.3 Research question 2b

The second RQ corresponding to Paper II was:

RQ2 *In the context of students’ learning in tutorial type group work:*

b) how can the theoretical framework of social semiotic be fruitfully combined with variation theory of learning in an analytical way to contribute to the theoretical understanding of students’ learning in group works?

To be able to answer this RQ and building on the theoretical frameworks presented in Chapter 3, I performed a lengthier analysis comprising both social semiotics and variation theory. The combination of these two theoretical frameworks to the analysis of the second data set led me to propose an analytical model for looking at the emergence of students’ learning in physics tutorial group work. I suggest that by using this analytical combination of social semiotics and variation theory on the second data set, I was provided with better analytical tools and I was thus able to gain a deeper understanding of students’ learning challenges, than what would have been possible from using any of the theoretical frameworks on their own. The details of this analytical application have been given in Section 5.2.3 and I will focus this subsection on discussing this combination.

In the episodes that were analysed for Paper II, the students in each group were arguing about the presence of a force that would either ‘keep the car from falling down’, or ‘keep the swing from going inside’. These particular sequences included discussions in each group that consisted of the use of multiple semiotic systems, including spoken language, sketches, mathematics, and gestures. A critical question that arise is then what the use of these semiotic systems could provide for the discussion and the collective learning within the group. I would like to bring this to the fore and focus this discussion on the different gestures that were introduced and used by both Carl and Frank. The analysis of students gestures can provide the researcher (or physics teacher) with valuable information about the student’s knowledge (Gregorcic et al., 2017; Scherr, 2008). However, studies on the use and meaning of such gestures to the collective learning progression within a group of physics students hasn’t been identified in the literature. I was, through a closer analysis of these gestures, able to identify the underlying meaning of the use of these gestures. I suggest that this identification could only be done by using the proposed combination of social semiotics and variation theory. The ‘underlying meaning’ that I refer to here can be explained in terms of dimensions of variation (DoVs). Carl used gestures to help Delia discern the changing velocity and acceleration of the car in combination with the force from the wall, by representing these aspects with his fingers to highlight the relationship between the three (see Table 6, line 312). In particular, I suggest that the discernment of the velocity, and how it changed, was of foremost crucial DoV. Whether Delia had experienced this particular DoV before or not, it nonetheless was aimed at helping her discern this DRA. A similar argument can be made about the gestures that were used by Frank when trying to make Gloria discern the changing velocity and acceleration of the rotating swing (Table 8, lines 182-186). In the analysis, I have shown how Frank and Carl both (1) in their relevance structure had identified velocity, and how it changes, as a critical DRA; (2) decided on suitable semiotic resources to showcase this DRA (in particular using gestures); and, (3) created variation within this DRA using semiotic resources (cf. Fredlund, Airey, & Linder, 2015). However, neither Gloria nor Delia were able to discern this particular DRA, which I interpreted as if they did not have velocity in their relevance structure at that specific moment when trying to identify the particular forces in the given problems (see also RQ2a).

By first analysing the learning sequences in my data using a social semiotic lens I was able to identify what semiotic systems and semiotic resources that were used within the students’ discussions as well as what DRAs that from the analysis were seen to be the focus of the students’ discussions. Following this I applied a variation theory lens to the identified sequences looking more closely into the used semiotic systems. I was from this able to identify in what ways the students applied the chosen semiotic resources to create necessary conditions for learning, i.e. by generating variation. Thus, I argue that the analytical combination of social semiotics and variation theory of learning turned out to be a fruitful tool enabling me to get a deeper insight and understanding into the learning challenges that students encounter when trying to bring the collective learning experience forward in physics group work. I thus suggest that social semiotics and variation theory complement and supplement each other in an effective way for qualitative analysis in PER.

6.4 Unified findings across papers and contexts

In the last section of this chapter, I would like to lift the discussion and look at my findings from Paper I and II from a broader perspective.

In the introduction to this thesis I discussed a previous theoretical analysis suggesting ways in which student learning could be enhanced (Fredlund et al., 2015). This theoretical analysis included generating purposeful variation and was proposed from the perspective of a teacher, i.e. teacher-constructed variation. The steps proposed by Fredlund et al. were built on a theoretical combination of social semiotics (to identify DRAs and choose appropriate semiotic resources) and variation theory (to generate purposeful variation). What I have found empirically through the research in this thesis is that these theoretically proposed steps are also spontaneously used by students in group work discussions. In line with variation theory, for learning to take place, a qualitative change in the relation between the knower and known must take place (Marton & Booth, 1997) and the essential terms describing this change are *variation, (disciplinary) discernment* and *simultaneity* (see also Section 3.2.1). I will come back to this below as it has bearing for the answer from RQ2b which shows that social semiotics and variation theory can indeed be fruitfully combined not only theoretically, as proposed by Fredlund et al. (2015), but also analytically.

What I find from my analysis is that the students' interactions in the learning sequences presented in the second data set can be, in parts, described using the three aforementioned constructs: variation, (disciplinary) discernment and simultaneity. Carl and Frank are identifying the changing velocity as a critical DRA and creates variation within this DRA—i.e. opens up this DoV—by using, in particular, gestures—both Carl and Frank has the velocity of the object in their focal awareness. This generated variation offers the other students the opportunity to discern this particular DRA from a disciplinary perspective—i.e. disciplinary discernment[35] (U. Eriksson et al., 2014a). As has been argued earlier, I suggest that the velocity was 'transcended' to both Delia and Gloria, i.e. it was not in their focal awareness. For a person to be able to discern a DoV which is being opened up, they <u>simultaneously</u> have to see both the transcended

[35] Remember Eriksson et al.'s (2014a) definition of disciplinary discernment: "noticing something, reflecting on it, and constructing meaning from a disciplinary perspective" (p. 170).

and the no-longer transcended. This means that the transcended DRA—changing velocity—needs to be experienced simultaneously with the velocity not being transcended. If students fail to do this, they will be unable to see this DoV, hence, "[l]ack of understanding is […] linked with being unaware of the potential for variation—seeing only that which is taken-for-granted [transcended]" (Booth & Hultén, 2003, p. 70). This way of understanding the data could explain Delia and Gloria's struggle to discern the critical DRA.

From the analysis I, thus, suggest that opening up a DoV in group discussions could afford learning—making learning possible—but is not an absolute criterion for learning—something that the empirical data in Paper II clearly shows. Nonetheless, "it can be said that a potential for learning is provided when a dimension of variation is opened—the conditions for learning are present to the group and to the problem-solving process" (Booth & Hultén, 2003, p. 70). From the above I thus conclude that variation, (disciplinary) discernment and simultaneity are important constructs that can be used as analytical tools to describe the situations that the students in my studies face when solving physics problems, either in groups or individually. Furthermore, I also find that to be able to make the appropriate disciplinary discernment, the students need to have the relevant DRAs in their relevance structure and simultaneously bring them into their focal awareness.

To exemplify what I mean I take the example of why the Moon always display the same side to an observer on Earth. To be able to understand this, one first need to discern this phenomenon and then realise that the Moon orbits around the Earth in about 30 days, and, at the same time, discern that it also rotates around its own axis in the same time period. These are the two DRAs that are critical to simultaneously discern in order to understand the observed phenomena. Only if a person is having both of these DRAs in their relevance structure (and simultaneously have them in their focal awareness) can they understand why the Moon always display the same side towards the Earth. This can also be seen as an example of where the 'parts' (orbital period and rotational period) make up the 'whole' and to be able to understand the 'whole' one also needs to understand the 'parts' (see Marton & Booth, 1997).

What my research additionally shows is how the important concept of relevance structure can be fruitfully applied to the analysis to be able to further understand the challenges of student learning in physics. The relationship between 'enacted relevance structure' and experienced variation proved to be an important aspect. I found that students who experienced variation within a DoV corresponding to a DRA that was not in their relevance structure, were less likely to discern this aspect (cf. McKenzie, 2002)—like for Delia and Gloria in Paper II. They were identified to having a static relevance structure—not seeing the velocity as being relevant—thus, although they were being presented with variation within this DoV, they were not able to discern this aspect. I propose that this can be understood in terms of that the students' relevance structure may act as a 'filter', preventing them from making the appropriate disciplinary discernment. Therefore, I suggest that students' relevance structure—what they perceive as being relevant for solving a particular task—may be added as an additional criterion towards understanding what is discerned in these situations. This view of a 'filter' can also be related to the findings from Paper I, where I identified students' individual level categories of relevance structure. These categories, combined with the understandings gained from Paper II, can explain why students might not discern the disciplinary use of algebraic signs.

Thus, a finding across the contexts that have been studied in this thesis, implies that even though teachers might present students with appropriate variation within the particular DRAs, disciplinary discernment of these DRAs in combination with students' relevance structure may prevent students from making the discernment. Hence, it is of foremost importance that research is directed towards learning more about how this 'filter' influences the conditions for learning. This discussion and direction of research falls outside of the scope of this thesis and I will come back to this topic in my suggestions for future work in the next chapter.

7 Contributions and implications

The aim of the research that I have presented in this thesis was to study the ways in which social semiotics and variation theory of learning fruitfully could be combined in an analytical way to increase understanding of students' learning challenges in physics. This was done by studying introductory level physics students in two different contexts; one- and two-dimensional kinematics.

After having introduced the research that have made up this licentiate thesis, both in terms of methodology, data collection and data analysis, and answered the research questions set up for this thesis, I would now like to turn my attention to the contributions these results bring to PER, and to the implications they bring for physics teaching and learning. I will end this chapter by looking into the future and briefly discuss ideas for future research.

7.1 Theoretical contributions

In terms of contributions to theories applicable to PER, in this thesis I have:

- showed how the theoretical frameworks of social semiotic and variation theory of learning fruitfully can complement and supplement each other in a powerful way to extend the analytical understanding of students' learning challenges in physics;
- showed how the theoretically proposed model for teachers to enhancing the possibilities for learning, suggested by Fredlund et al. (2015), are also empirically applied by students;
- in relation to the three steps mentioned above, showed how relevance structure plays a major role in what students are able to discern;
- initiated a discussion about how relevance structure and disciplinary discernment theoretically can be related to each other to understand learning challenges in physics; and,

- showed how, in the particular context of circular motion, two approaches to viewing the problem influence the students' ability to discern the critical DRAs.

7.2 Methodological contributions

In terms of methodological contributions, I have, in this thesis:

- showed how student-created semiotic resources, such as gestures, can provide researchers with valuable information about students' conceptual understanding; and,
- showed how students' relevance structure can be used as a way to understanding learning sequences in group work.

7.3 Implications for teaching and learning

Based on the results and discussion presented in this thesis, the suggested implications for physics teaching and learning are that:

- teachers need to focus on helping their students to develop, for the particular problem, the correct relevance structure and realize that what students find relevant for solving the particular problem will affect their success in doing so;
- based on the results from Paper I, the use of algebraic signs needs to be more explicitly unpacked for students if they are to develop the correct relevance structure for how to use plus and minus signs in one-dimensional vector-kinematics; and,
- based on the results from Paper II, the two suggested approaches to viewing circular motion problems needs to be given consideration in the teaching. From this it also follows that teaching and learning needs to additionally focus on the use of different reference frames in the context of circular motion.

7.4 Future work

From the findings that I have discussed in this thesis, there are many different possible ways forward. In this final section of my thesis I will briefly discuss possible ways in which I can continue to develop the research which has been presented in this thesis and in Papers I and II.

One such interesting way forward is to continue to explore the analytical combination of variation theory and social semiotics from a theoretical perspective by discussing how constructs such as relevance structure, dimensions of variation and disciplinary relevant aspects may be theoretically combined. This theoretical combination can be added as a pertinent piece of the social semiotic 'puzzle' to further describe and understand learning challenges in university physics teaching and learning. I have in this thesis explored the combination of variation theory and social semiotics and I believe that there is much more to add to this combination. Thus, I am interested in further exploring this combination in the future, for example, by further studying the relationship between relevance structure and disciplinary discernment, as mentioned in Section 6.4.

I have found that students' relevance structure may act as a filter against discerning experienced variation. However, what is yet not understood is how this filter might be overturned. Thus, a RQ question for future research might be formulated as: "*How can physics teaching and learning help students to transform their individual relevance structure to overcome the 'filter' that the relevance structure has to their possibility to discern the disciplinary relevant aspects*".

Lastly, I will aim to be focusing my research towards providing physics teachers with theoretical tools to better help their students overcome any challenges in learning physics that they might have.

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Appendix A

Questionnaire regarding student' experiences of the usage of algebraic signs in kinematic problem-solving

This questionnaire is a part of a study where participation is completely voluntarily and where you, through handing in your answers, agree that this information may be a part of my analysis and the reporting of it. Any personal information you provide will only be handled by me and will not, in any way, be linked to you personally, in either my analysis or report of the result.

This questionnaire is created as a part of my bachelor's project where I aim to find out how students are experiencing the use of algebraic signs (+ and -) in order to solve problems in kinematics. The object of this project is to be able to, in terms of already conducted international research, categorize these experiences in order to contribute to the development of the teaching and learning of kinematics.

Instructions:
When you answer the questions on the following pages, please carefully **explain your reasoning**. There is no interest in identifying the "right" or "wrong" answer, but to understand how the use of signs is being looked at by students. Therefore I am asking you to, on your own, answer the questions through giving your spontaneous answer. In other words, do not discuss the answer with your friends or go back and change your answers.

As a second part of my study I would like to hold a 15 minute long discussion with you to obtain better understanding of your experiences. If you would like to help me with my study through participating in a discussion like this, please write your e-mail address on the line below and I will contact you to complete this. I would like to point out that also these discussions will not provide any personal connection to you either in my analysis or report of the result. This information will only be handled by me.

E-mail: ____

If you have any questions about your participation or if you want to know more about this study, please do not hesitate to contact me!

Thank you for your participation!
Moa Eriksson
moer7464@student.uu.se

Appendix B

Concession / Medgivande

[Svensk version följer längre ner,
Swedish version follows on the next page]

During your studies in physics and/or astronomy you may be asked to participate in physics and astronomy education research projects. By signing this document you are giving your explicit consent for us to use data that you provide in audio, video, or written surveys for research purposes at the Physics Departments at Lund University and Uppsala University, Sweden. We guarantee total confidentiality in accordance to Swedish law and the guidelines from the Swedish Research Council.

The analytic use of the data will be to answer specific research questions dealing with aspects of learning physics and/or astronomy. The only linked personal information that may be used in the analysis and its reporting are the answers you give to the questions about age, gender and academic background. We guarantee that no other personal links will be made to this information. With this guarantee you are also consenting to: (1) having the data shared digitally amongst our research groups and stored on our computers; and, (2) to have the data used in the verbal and written reporting of our analysis. This includes digital and paper publication[1] of our results. The reporting of these results may also include some video/audio excerpts and quotations from your answers that you provided in the data collections. If we would like to use the material in another way, we will contact you for an extended consent.

Contact addresses are:
Urban Eriksson, Ann-Marie Pendrill, Lassana Ouattara
National Research Center for Physics Education
Department of Physics
Lund University, Lund

E-mail: firstname.surname@fysik.lu.se

[1]Publication takes place mostly in scientific journals and in research related conference proceedings. In all cases both digital and paper publication may take place.

Under dina studier i fysik och/eller astronomi kan du bli ombedd att delta i fysik- och astronomididaktiska forskningsprojekt. Genom att underteckna det här dokumentet ger du ditt uttryckliga medgivande för oss att använda data som du tillhandahåller i form av t ex ljud-, video- eller skriftliga datainsamlingar för forskningsändamål på Institutionerna för fysik, Lunds universitet och Uppsala universitet. Vi garanterar total konfidentialitet i enlighet med svensk lag samt riktlinjerna från Vetenskapsrådet.

Den analytiska användningen av data Du lämnar avser svara på specifika forskningsfrågor som rör aspekter av lärande i fysik och/eller astronomi. Den enda länkade personliga informationen som kan användas i analysen och dess rapportering är svaren du ger till frågorna om genus, ålder och akademisk bakgrund. Vi garanterar att inga andra personliga uppgifter kommer att länkas till denna information. Med denna garanti samtycker du även till att (1) låta data digitalt delas mellan medlemmar i vår forskningsgrupp och att data lagras på våra datorer; och, (2) att vi får använda dessa uppgifter i den verbala och skriftliga rapporteringen av vår analys. Detta inkluderar digitala- och artikelpublikation [2] av våra resultat. Rapporteringen av dessa resultat kan också innehålla video/audio samt citat från dina svar som du gav i datainsamlingen. Om vi skulle vilja använda material på annat sätt kommer vi att kontakta dig för ett utvidgat tillstånd.

Kontaktuppgifter:
Urban Eriksson, Ann-Marie Pendrill, Lassana Ouattara
Nationellt ResurCentrum för Fysik
Fysikinstitutionen
Lunds universitet, Lund

E-mail: förnamn.efternamn@fysik.lu.se

Name / Namn E-mail / E-post

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[2] Publicering sker huvudsakligen i vetenskapliga tidskrifter och i forskningsrelaterade konferenshandlingar. I alla fall kan både digitalt och artiklar publiceras.

Appendix C

Problem 1: The motion of a rolling ball

A small ball rolls along a smooth surface (ignore friction). When the ball has rolled 2m, it reverses when it hits a barrier (no energy is lost during the collision) and it rolls back to its original position. For the questions below, please **explain** your reasoning carefully.

Before: 

After: 

1.1: Is there any difference to the motion of the ball before and after the turn? Explain the **meaning** of any algebraic signs (+ or -) that you used.

1.2: Is direction important to specify the motion of the ball? Explain.

1.3: Describe the distance and displacement of the ball before and after the turn. Explain the **meaning** of any algebraic signs (+ or -) that you used.

1.4: Describe the speed and velocity of the ball before and after the turn. Explain the **meaning** of any algebraic signs (+ or -) that you used.

1.5: Describe the acceleration of the ball before and after the turn. Explain the **meaning** of any algebraic signs (+ or -) that you used.

Problem 2: Velocity and acceleration of a car chase

Imagine the following sequence:

(1) A police car is standing by the side of the road at the intersection between Dag Hammarskjölds väg and Kungsängsleden when she sees a Volvo travelling at a constant speed through a red light.

(2) The police car immediately starts chasing the Volvo, along a straight part of the road, accelerating from rest until reaching a maximum chasing speed.

(3) The officer holds this speed until she is alongside to the Volvo.

(4) She turns on the blue light signalling to the Volvo to pull over. The driver of the Volvo starts to slow down, the police car also slows down, staying alongside the Volvo.

(5) Both cars finally stop by the side of the road.

2.1: For the different parts of the sequence (1)-(5) above, **sketch** the velocity of the **police car** using arrows, and signs if appropriate.

(1) (2) (3) (4) (5)

2.2: Explain the **meaning** of **any** algebraic signs (+ or -) that you may have used.

2.3: For the different parts of the sequence (1)-(5) above, **sketch** the acceleration of the **police car** using arrows, and signs if appropriate.

(1) (2) (3) (4) (5)

2.4: Explain the **meaning** of **any** algebraic signs (+ or -) that you may have used.

2.5 Supposed the police car **turns around** and follows the **exact same** sequence in the other direction.

2.5.1: For the different parts of the sequence (1)-(5), **sketch** the velocity of the **police car** using arrows, and signs if appropriate.

(1) (2) (3) (4) (5)

2.5.2: Explain the **meaning** of **any** algebraic signs (+ or -) that you may have used.

2.5.3: For the different parts of the sequence (1)-(5), **sketch** the acceleration of the **police car** using arrows, and signs if appropriate.

(1) (2) (3) (4) (5)

2.5.4: Explain the **meaning** of **any** algebraic signs (+ or -) that you may have used.

2.6 Are there any differences between the arrows and/or signs that you used to describe the velocity and acceleration respectively in the above questions? If so, please explain.

Appendix D

Possible solutions to the problems from the second data set

To be able to understand and solve circular motion problems, students need to discern certain disciplinary relevant aspects (DRAs). In this appendix I will present these DRAs and describe possible solutions to the two circular motion problems that were used in the second data set.

General comments

A general solution to circular motion problems require that students are able to apply Newton's second law (N2) to the problem:

$$\Sigma \bar{F} = m\bar{a}.$$

Students also need to realize that the object in a circular motion is undergoing an acceleration, i.e. that the velocity of the object keeps changing (Figure 1). If the time interval between $\bar{v}_1$ and $\bar{v}_2$becomes infinitesimally small, $\Delta\bar{v}$ will point towards the centre of the circle.

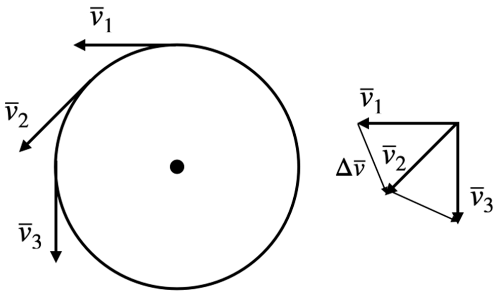


Figure 1. Figure showing the changing velocity in a circular motion.

In a uniform circular motion problem, the magnitude of the acceleration of the object remains constant and is directed towards the centre of the circle. Thus, the resulting force—the *centripetal force*, F_c—given from N2, is also directed towards the centre of the circle.

If viewing the problem in an inertial frame of reference using a cartesian coordinate system, one approach is to apply N2 to forces in x- and y-direction separately—i.e., $\Sigma\bar{F}_x$ and $\Sigma\bar{F}_y$.

Vertical circular motion

In this problem the students were asked what forces are acting on the car at the lowest (point A) and highest (point B) point in a vertical loop (Figure 2). The object in this problem is in uniform circular motion. Somewhat unrealistically, the speed of the object stays the same throughout the motion. Hence, the size of the acceleration towards the centre of the circle, the centripetal acceleration, remains constant. For the bottom and top-most points in the loop there are two forces acting on the object—the gravitational force (mg) and the normal force (N). Thus, applying N2 yields the vector equation

$$\Sigma\bar{F} = \bar{N} + m\bar{g} = m\bar{a}.$$

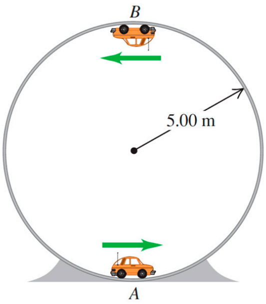


Figure 2. The given diagram used for the problem in Episode 1

Since the forces acting on the object at points A and B both are directed radially, there is only a y-component to the resulting force, $\bar{F}_y = F_c$ (see Figure 3).

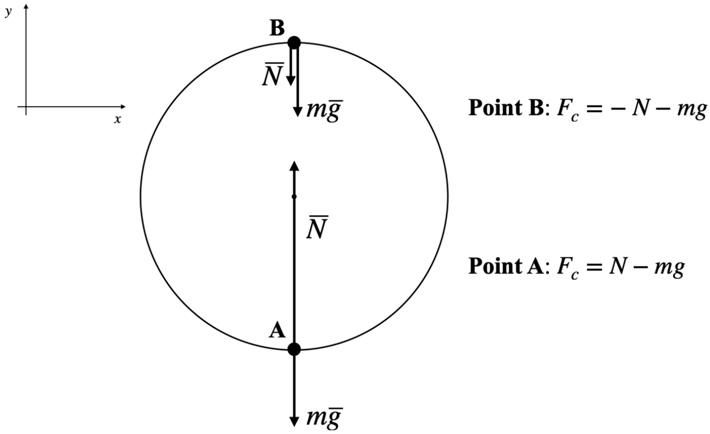


Figure 3. Force diagram for forces acting on the car at points A and B.

In the force diagram given in Figure 3, we see that the resultant force, F_c, in both Points A and B, has the same size and is pointing towards the centre of the circle.

Horizontal circular motion

In this problem the students were asked to find the forces acting on a person in a swing ride. The swing and rider in this problem is in uniform circular motion, i.e. the speed of the swing and rider is constant and thus the centripetal acceleration stays the same throughout the motion. For every point in this circular motion, there are two forces acting on the object—the gravitational force (mg) and the tension from the rope (F_T) (see Figure 4). Thus, N2 yields

$$\Sigma\bar{F} = \bar{F}_T + m\bar{g} = m\bar{a}$$

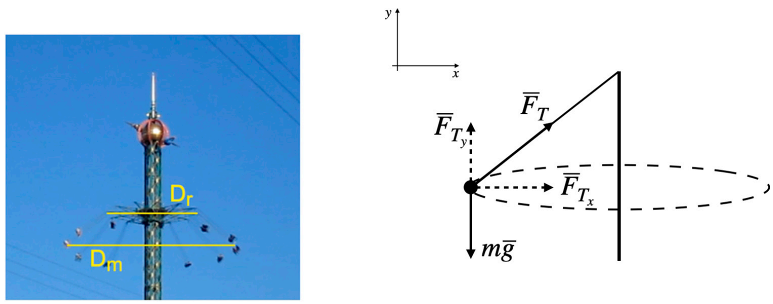
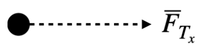


Figure 4. Problem figure and force diagram for the forces acting on the swing and rider.

Since the forces acting on the object in the circular motion at this particular moment shown in Figure 4 are directed in both x- and y-direction students are expected to divide the force equation from N2 into two cases where $\bar{F}_T = (F_{T_x}, F_{T_y})$:

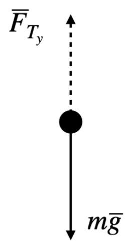
- Sum of forces in x-direction:

$$\Sigma\bar{F}_x = \mathrm{F}_{\mathrm{T_x}}$$



- Sum of forces in y-direction:

$$\Sigma\bar{F}_y = F_{T_y} - mg$$



Since the swing and rider is only going in a horizontal circular motion, the y-component of the acceleration is zero, hence the resultant force in the y-direction is also zero. Thus, the only non-zero resultant force is the x-component of the tension force, F_{T_x}, which in this case is the centripetal force, F_c, acting on the swing and rider.

Conclusion

From the suggested problem solutions given here, it is concluded that DRAs for the problem of finding the forces that are acting on the objects in circular motion given here include the velocity, the change in velocity (i.e. acceleration), normal force, gravitational force and the tension, which are all vectors.

Paper I

Towards understanding learning challenges involving sign convention in introductory level kinematics

Moa Eriksson[1,2], Cedric Linder[2], Urban Eriksson[1]

[1] *Department of Physics, Lund University, Lund, Sweden, 22100*
[2] *Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden, 75120*

Coming to appropriately appreciate the meaning of algebraic signs is an important aspect in introductory kinematics. However, in this educational context, the "disciplinary relevant aspects" of algebraic signs across vector and scalar representations are extremely difficult to discern. Our study explores the "relevance structure" that one-dimensional kinematics problems evoked for introductory level university physics students across two very different educational systems which have, in PER terms, progressive teaching environments: Sweden (n=60) and South Africa (n=24). The outcomes of two previous PER studies are used to provide the analytic basis for formulating categories of relevance structure. Aspects of a contemporary PER-developed social semiotics perspective (referred to here in terms of communication practices) are used to discuss implications for teaching in the given educational context of introductory kinematics.

I. INTRODUCTION

Research aimed at understanding learning challenges involving algebraic signs in introductory level kinematics has been rare. However, algebraic signs have been identified as presenting a significant learning challenge for physics students [1-4]. The aim of the research reported on here is to contribute to addressing this deficit by drawing on the idea that a core part of the process of learning involves students learning to "read" the situated physics-ways of representing *disciplinary relevant aspects* in order to understand and use them appropriately [5-10]. From this perspective, such "reading" is thought of as being about recognizing a situation that requires being experienced in a particular disciplinary way. In other words, there is a disciplinary awareness – a discernment – that is called for that is directly related to the context, which includes the way the parts of this awareness are seen to relate to one another [5,9] (i.e. how it gets read in relation to how it gets used). The context is central here because what emerges in a person's "focal awareness" for a given context is a function of the experience of that context (both past and present) and how that experience has been made sense of. The way a person "reads" a situation can be analytically referred to in the broader "student learning" literature as a person's *relevance structure*. This is because *relevance structure* is "the person's experience of what the situation calls for, what it demands. It is a sense of aim, of direction, in relation to which different aspects of the situation appear more or less relevant" [11] – what gets focused on by them in a given context. Thus, for the purposes of our study the concept of relevance structure presents an opportunity to further explore learning challenges involving algebraic signs by using a study situated in introductory level kinematics problem-solving regardless of where the education takes place.

A. Research question

Our study posed the following research question: What are the individual-level categories of variation of experiencing relevance structure with regard to algebraic signs (+ and –) in introductory kinematics problem-solving in university physics education?

II. METHOD

Our method built on the analysis of a set of collective-level[1] categories obtained by Eriksson [12], which drew on the work by Govender [2,3], in the area of introductory kinematics. Our point of departure from these studies was bringing the focus of interpretation to the individual level for the purpose of iteratively [13] constructing categories of relevance structure [14].

The participating students were drawn from two introductory physics classes, one at a Swedish university and the other in a South African. These classes were chosen on the basis that the educational environments in both settings were, from a PER perspective, progressive (in terms of the teacher being familiar with the educational benefits associated with knowledge of PER) and that the students in these classes came from different socio-economic backgrounds. In total, 84 students participated with appropriate ethical consent. Both groups of students had completed coursework that involved using algebraic signs for vector calculations in kinematics.

The data set was made up of a combination of students' individual written questionnaire answers and verbatim transcriptions of follow-up interview discussions.

The analysis proceeded as follows: first, a questionnaire was given to the students which contained two one-dimensional straight-line scenarios (see Fig. 1) where

[1] The collective-level points to "identifying the very [actual] ways in which something may be experienced" [11] and since this was the principal aim of our study, no individual classification was done.

students were asked to explain the meaning of any algebraic signs that they used in their expressions of displacement, distance, speed, velocity, and acceleration for a constant velocity situation; and, velocity and acceleration for a changing velocity situation. From this set of answers a "purposeful sample" [15] of students was chosen for semi-structured follow-up interviews about the way(s) they had answered these two questions – a stimulated recall research procedure [16]. This combined data set was then used to construct categories of relevance structure. In line with the epistemological stance that grounded our study [11], the procedure for this followed a naturalistic qualitative analytic method [13] in that it involved a constant comparative approach made up of emerging coding in relation to sorting into category groups. This ended when redundancy was reached. The Swedish and South African data were coded separately and then merged together for the final analysis. The entire coding process was independently cross-checked by PER colleagues.

III. RESULTS

Our methodology yielded four different categories of relevance structure (see Table I) that the participating introductory level physics students evoked when reading and using signs (+ and –) in one-dimensional kinematics problems. The same variation of relevance structure was observed for both the Swedish and the South African data sets, i.e. they were independent of educational context.

We propose that the categories have an inherent hierarchy that spans from the least advanced way of reading and using signs (Category A) to the most advanced way (Category D).

TABLE I. Categories of relevance structure for algebraic signs in introductory level kinematics.

Category of relevance structure:	**"Reading" – Variation described in:**	**"Use" – Focus of intention (relevance structure perceived):**
A	No specific assignment of signs	• Nothing necessarily specific in kinematics terms
B	+ and – assignment (single purpose)	• Representing changing magnitude
C	+ and – assignment (dual purpose)	• Representing magnitude in the case of acceleration • Representing direction in the case of velocity
D	+ and – assignment (dual purpose)	• Representing direction by convention • Representing direction by choice

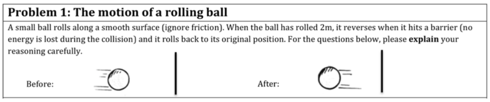


FIG 1. The first problem given on the questionnaire. The problem context is the following: "A small ball rolls along a smooth surface (ignore friction). When the ball has rolled 2m, it reverses when it hits a barrier (no energy is lost during the collision) and it rolls back to its original position."

In the summary description of the results that follow, we present selected excerpts from the data that make up the different relevance structure categories.

Note: Q and I refer to questionnaire and interview sources respectively, while S refers to student's answers from both. Each "box" represents a stand-alone example.

For the purposes of some of the examples used in this paper, the Swedish has been translated into English.

A. Algebraic signs do not necessarily have specific relevance in kinematics

Students that experience this relevance structure do not consider algebraic signs to be needed specifically in kinematics. This is because directional signs can be replaced by directly referring to the given direction linguistically. For example:

> Q: Explain the speed and velocity of the ball before and after it turns. Explain the meaning of any algebraic signs (+ and –) that you use.
> S: *[…] I think that + and – seems a bit unnecessary. Why don't [we] just say a* ***motion to the right or left****?*

> I: Would [the velocity] have any signs in this case?
> S: *No, not when we have decided forward as left. I don't really think in terms of plus and minus, but I think* ***in terms of right and left****.*

B. When an algebraic sign is assigned to a kinematic unit it is seen as being relevant for representing a changing magnitude

Students that experience this relevance structure appear to be connecting their way of reading algebraic signs in everyday life in relation to getting bigger or smaller. For example:

> I: What do you think that the signs for velocity show?
> S: *Plus to me means that it is* ***going faster****, that the velocity increases. And minus should then be the opposite, that the* ***velocity simply decreases****.*

> S: *I experience plus as something that is* ***getting bigger*** *and minus as something that is* ***getting smaller****.*

This category of relevance structure illustrates how students can get to experience signs as having a single purpose of indicating changing magnitude, often connecting the sign for acceleration to an increase or decrease of velocity and vice versa.

I: What does the signs for acceleration mean to you?
S: ***Increase or decrease of velocity***.

I: So when [the car] goes from some velocity to no velocity [what does it mean to you]?
S: *Then it is deceleration, I'm thinking negative acceleration.*

C. The assignment of algebraic signs in kinematics has dual relevance: for representing changing magnitudes in the case of acceleration, and for representing direction in the case of velocity

Students that experience this relevance structure see algebraic signs as having a dual purpose in kinematics. In the case of velocity, they indicate direction, and in the case of acceleration they indicate magnitudes.

S: *[I]n velocity the signs only specify the* ***direction of motion****, however in acceleration it means* ***speeding [up] or slowing [down]***.

S: *[W]hen it comes to velocity + and –* ***only show direction****. When it comes to acceleration they* ***only show the acceleration's increase or decrease*** *and don't take direction into consideration. Why it turned out this way I don't know!*

D. The assignment of algebraic signs in kinematics has dual relevance: for representing direction by convention, and for representing direction by choice

This category of relevance structure illustrates how students can get to experience signs as being functional for indicating how direction gets to be assigned; by convention or by choice. Direction by convention is often stated explicitly, as illustrated in the following examples:

Q: Is the direction important to be able to decide the motion of the ball? Explain.
S: *[…] The motion is positive, if the direction of the ball* ***is to the right*** *[as] in this case.*

Q: Is there any difference to the motion of the ball before and after the turn? Explain the meaning of any algebraic signs (+ or –) that you used, if any.
S: *The motion is negative (–) after [the turn]. Because its motion is in* ***the opposite direction***.

Similarly, representing direction by choice is illustrated in the following transcript excerpts:

I: And what do the signs mean to you in physics?
S: *It is the direction, partly. Or the* ***direction in relation to how you decide on it***.

Q: Is there any difference to the motion of the ball before and after the turn? Explain the meaning of any algebraic signs (+ or –) that you used, if any.
S: *No difference except that directions are opposite.* ***If we choose*** *the initial direction as positive (+) then the other direction after the ball hit the barrier would be negative (–).*

IV. DISCUSSION

Students' relevance structure – how they "read" algebraic signs in kinematics – was explored. The results indicate that the students had largely made sense of how they have experienced algebraic signs being used in kinematics formulations without direct reference to a coordinate system. Furthermore, the idea of calculation-invariance associated with the free choice of a coordinate system was seldom found in the data set. From a social semiotics perspective [17], we propose that this is partially a consequence of a lack of appreciation for the importance that communication practices play in the teaching and learning of physics [e.g. see Ref. 8], such as, in our case, when introducing students to one-dimensional kinematic problem-solving. Discussion with nine introductory physics lecturers from both countries together with the inspection of five popular introductory level textbooks lead us to anecdotally propose the following: that the communication practices used to exemplify problem solving in introductory kinematics have the distinct potential to lead to "fuzzy" readings of algebraic signs and the understanding of their usage in one-dimensional kinematics. Thus, such communication practices arguably contribute to the personal constitution of the range of relevance structure categories presented in this article. Examples of the kind of communication practices that may lead to "fuzziness" that we encountered are:

1. one-dimensional kinematics being dealt with before doing a generalized introduction to vectors while implicitly drawing on fundamentals that arise out of the mathematical application of a coordinate system;
2. the components are not always portrayed as scalars both in words and pictorially. Here, the signs emerge from a parallel or anti-parallel alignment of the so-called "component vector" with the given coordinate axis;
3. the use of unit vector notation as the route to obtaining one-dimensional scalar equations with their correct signs where moving from the unit vector to scalar representation is taken to be unproblematic; and,
4. in stark contrast signs were simply assigned as a convention linked to direction.

In all four of these illustrative communication practices, pictorial representations get used alongside mathematical and linguistic representations, and it appears as if a basic understanding of vector algebra is taken to be self-evident.

There have been several recent PER contributions that have started to model links between gaining access to what is educationally critical – *disciplinary relevant aspects* [9] –

for a given *object of learning* [11] and the representations that get used to share this knowledge (for a summary see Ref. [17]). There has been work that advocates students be explicitly taught to work competently with a set of representational forms and there have been proposals that there is a critical combination of representations (i.e. semiotic resources [17,18] such as graphs, diagrams, sketches, figures, mathematics, specialist language, etc.) that are needed to give an encompassing access to the disciplinary relevant aspects of a given object of learning. From such a social semiotic standpoint, even when an explicit effort is made to prevent the "fuzziness" referred to earlier, other challenging communication practices can emerge, such as drawing a single component coordinate system using a straight line with an arrow head added as some texts do (some texts add a zero to indicate some kind of one-dimensional origin). However, should the teaching practice follow a communicative format [19] to bring out awareness of the disciplinary relevant aspects and to work through the relevance structure categories reported here, then we believe that the learning possibility could be optimized by design. We propose that such design be built on the idea that: in order to learn to experience something in a new and meaningful way, a person needs to become aware of the critical aspects that the new way of experiencing is built on. Such awareness can only become possible through particular communication practices.

In other words, we propose that for such a crafting of practice, teachers need to give more consideration to how the form and content of the representations that get used to make up their communication practices affect the possibility for students to better discern what is important – the disciplinary relevant aspects.

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[14] At a certain level, a methodological relationship can be seen between the PER-established framing-resources perspective [e.g. 14a-c] and the relevance structure construct that we used for our analysis. It was our principle analytic focus – the contextual discernment and the way the parts of this awareness were then seen to relate to one another – that led to our choice of relevance structure. Its strength as an analytic tool here can be seen when consideration is given to its epistemic grounding which is an anatomy of awareness. In contrast, the epistemic grounding of the PER framing-resources perspective is discourse analysis (one of the principal sources is [14d]), where the central focus is not necessarily on disciplinary relevant aspects [e.g. 14e].
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Paper II

Using social semiotics and variation theory to analyse learning challenges in physics: a methodological case study

Moa Eriksson[1,2], Urban Eriksson[1], Cedric Linder[2,3]

[1] National Resource Centre for Physics Education, Department of Physics, Lund University, Lund, Sweden
[2] Division of Physics Education Research, Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden
[3]Department of Physics and Astronomy, University of the Western Cape, Cape Town, South Africa

Abstract

In this paper we examine an analytical combination of two theoretical frameworks—social semiotics and the Variation Theory of Learning—as a new way to obtain additional insights and understanding of students' learning challenges in physics. As a case study, students were video recorded during a group problem-solving session while working on two circular motion tutorial problems. Through the combined analytic approach, we were able to identify students' *enacted relevance structure* and use this to better understand how individual student's relevance structure affected the emergent learning within the group. We also illustrate and discuss how this analytic combination can provide additional teaching insights and how these insights could be used to enhance teachers' understanding of their students' learning.

Introduction

Social semiotics has been shown to be a powerful tool that can be used to understand student engagement with physics tasks. Closely linked to this analytical framework is the Variation Theory of Learning (VTL) that points to ways of teaching. While both have been widely used in many contexts the two have not been analytically combined. Although the idea has been proposed (Linder, 2012) and later theoretically supported from the work of Eriksson (2014) and Fredlund (2015), there are no published examples of how social semiotics and VTL would function together as new analytical tool to study learning in an area such as physics. This paper uses data from a case study involving physics students working in groups to solve tutorial problems and the data is made up of multimodally transcribed group discussions about solving a given tutorial problem. The analysis of the data and its discussion illustrates how a more comprehensive and insightful understanding of interactive student learning can be attained. The physics learning context was selected as it is situated in both group work and an area of introductory level physics that has long been seen by educators to be challenging for students to master conceptually (for example, see Arons, 1981; Gardner, 1984; Pendrill, Eriksson, Eriksson, Svensson, & Ouattara, 2019; Viennot, 1979; and Warren, 1971, 1979).

In Part I of the paper we present a summary of the key features of social semiotics and VTL that are pertinent to the analysis presented. Part II of the paper presents the data. The data is presented in the form of two different episodes, one where students are working on a circular motion problem in the vertical plane, and the other of students working with a circular motion problem in the horizontal plane. Part III presents a two-part discussion that deals with arising analytic considerations and considerations for teaching. Finally, Part IV gives a short conclusion.

Part I: Theoretical frameworks

1.1 Social semiotics

The semiotics perspective developed for investigating important relations between physics teaching and learning (for a recent summary see, Airey & Linder, 2017), which we use for our analysis, is a perspective that draws on the broader social semiotic research community (for example, Jewitt & Kress, 2003; Kress & Mavers, 2005; and van Leeuwen, 2005). This broader community focuses on the form and content of communication practices that particular social groups have developed and use (in our case, the discipline and classroom practices of physics). Put another way, the social semiotics perspective that we use is an emerging Physics Education Research (PER) tool for "the study of the development and reproduction of specialized systems of meaning making in particular sections of society" (Airey & Linder, 2017, p. 2) as it relates to the teaching and learning of physics. Here, all communication and its consequent facilitation of meaning making is situated in a particular collection of semiotic systems and the resources that these systems offer for a particular context of communication and sense making (for an example from the physics student laboratory see Volkwyn, Airey, Gregorcic, Heijkensköld, & Linder, 2018). Semiotic resources that can be found within physics are typically derived from the following semiotic systems: spoken and written language, mathematics, diagrams, gestures and apparatus. This perspective has been used in multiple studies recently as a way to understand student learning in various physics contexts (see Eriksson, 2014; Euler, Rådahl, & Gregorcic, 2019; Fredlund, 2015; Volkwyn, Airey, Gregorcic, & Heijkenskjöld, 2019; and Weliweriya, Sayre, & Zollman, 2019) and this paper extends these efforts by using it alongside VTL (Marton, 2015; Marton & Booth, 1997) (see Section 1.2) as an analytic tool.

To constitute the needed meaning that underpins the appropriate understanding of a particular phenomenon in physics, certain vital aspects from a physics perspective—*Disciplinary Relevant Aspects* (DRAs)—need to be considered. Fredlund, Airey and Linder (2015, p. 2), following Fredlund, Linder and Airey (2015) and Fredlund (2015), define Disciplinary Relevant Aspects as "those aspects of physics concepts that have particular relevance for carrying out a specific task" (which in our case is exemplified by the formulation of appropriate understanding and utility of particular cases of circular motion). These DRAs need to become an integral part of students' "focal awareness" (Marton & Booth, 1997, see Section 1.2) in all physics learning situations, i.e. the DRAs need be "discerned" by the students for a given physics learning situation, or task, in order for them to constitute the intended meaning appropriately and for the students to successfully solve the given task. The consequence of such a view of learning is that the learning environment needs to present students with opportunities to discern the needed DRAs, particularly when they are not directly visible. A recent example of a study exploring such an environment is Fredlund, Linder, Airey and Linder (2014) who situate the exploration in the "unpacking" of complex ideas and actions. While such unpacking has been shown to be difficult for students to do themselves (Eriksson, 2014, 2019; Fredlund, 2015; Fredlund et al., 2014) there is a study that has illustrated how, for an interactive learning environment, the participating students get to do this for themselves (Ingerman, Linder, & Marshall, 2009). The work reported on in this paper builds on this possibility.

1.2 The Variation Theory of Learning

The second analytical tool used for the analysis given in this paper is the Variation Theory of Learning (VTL) (Marton, 2015; Marton & Booth, 1997; Marton & Tsui, 2004). The setting for our introduction to VTL is that knowledge is constituted in terms of relations between the knower and the known. From here, learning becomes being about experiencing *qualitative change* in these relations. Adopting such a perspective means that what becomes analytically interesting is the "how" and "what" of making the experiencing of some aspect of physics modelling possible "when it appears in a novel situation in a particular way—which goes beyond the other ways in which [the person] has been capable of experiencing the phenomenon" (Marton & Booth, 1997, p. 142). In other words, we use this perspective to claim that learning has started to take place when the relationship between the person and the phenomenon can be seen to change. In other words, when "the learner has become capable of discerning aspects of the phenomenon other than those she had been capable of discerning before, and she has become capable of being simultaneously and focally aware of other aspects or more aspects of the phenomenon than was previously the case" (Marton & Booth, 1997, p. 142). This is where VTL comes into the picture.

VTL is a very rich and powerful perspective that is used widely internationally across many different types of teaching and learning contexts, and it is thus not possible to give a comprehensive overview here. Instead, we refer interested readers to Marton (2015); Marton and Booth (1997); Marton and Pang (2013); and Marton and Tsui (2004) which collectively provide both an overview of the theory, research in the area and its broader use in educational research. Below are the central underpinning aspects of VTL needed for this paper:

(1) it is an approach to viewing formalised learning which is grounded in *acquiring new meaning* as a function of noticing something that was not noticed before or seeing that particular aspect in a new way. This is referred to as what is in *focal awareness*;

(2) such meaningful noticing is formulated as the *discernment that arises out of experiencing differences against a background of sameness* (rather than vice-versa). Basically, discernment is made up of two components: experiencing variation in ways that facilitate noticing something and then making meaning from what is noticed in a new way. In other words, getting to see things in fundamentally new ways as a function of experiencing dimensions of variation that have been opened around some critical feature of a phenomenon or even the phenomenon itself;

(3) from a disciplinary point of view, acquiring such new meaning calls for the discernment of the *critical aspects* that underpin the new meaning (in our case, the DRAs of circular motion for the task at hand);

(4) the possibility of *discernment that arises out of experiencing differences against a background of sameness* calls for *experiencing particular kinds of variation—dimensions of variation* (see below); and,

(5) aspects are considered *not* to be in *focal awareness* when they are:

- *transcended* – overlooked or not discerned at all; and,
- *taken-for-granted* – things that have been discerned previously and subsequently, unreflectively assumed to be applicable (or not), in the new situation.

The summary given above yields three important constructs for variation theory—*variation*, *discernment* and *simultaneity*:

> "Variation" is an essential aspect of learning in this sense: that learning occurs (things are seen in distinctly new ways) when a dimension of variation opens around a phenomenon or aspect of a phenomenon that once was taken-for-granted. "Discernment" is the act of seeing this no-longer-taken-for-granted phenomenon or aspect of a phenomenon in a new light. "Simultaneity" – seeing both the once-taken-for-granted and the no-longer-taken-for-granted – is demanded for the dimension of variation to open. Lack of understanding is thus linked with being unaware of the potential for variation – seeing only that which is taken-for-granted. (Booth & Hultén, 2003, p. 69)

The summary given "translates" into seeing learning in an area such as physics as being about what is needed to get to see things in specific, usually new, ways and then being able to bring what is relevant from this learning into focal awareness for a particular area of understanding, application, task or practice. In variation theory terms, such learning only becomes possible when a "dimension of variation" is opened for a disciplinary relevant aspect that has been transcended or taken-for-granted or both of these. Here, simultaneity is vital: the once transcended or taken-for-granted must be simultaneously seen with the no-longer-transcended or the no-longer-taken-for granted for a dimension of variation to be opened (for further discussion of simultaneity, see Section 2.1.1). To discern a particular aspect not discerned before, or to discern this aspect in a different way, often means that one needs to experience *different facets (or values)* of that aspect simultaneously in order to be able to differentiate it from other aspects. For example, in introductory level classical physics, students need to be able to differentiate between a "system" made up of one or more bodies that are being observed kinematically in an *inertial frame of reference* and in a *non-inertial frame of reference*. Such a differentiation calls for the discernment of disciplinary relevant aspects of the system under study. At the same time the discernment of some of these DRAs may have several features that also need to be discerned as part of the meaning making experience. In such cases, for the discernment of each of these features a *dimension of variation* will have (had) to be experienced. For instance, an inertial frame of reference has a distinct aspect—it moves with constant velocity—and a system made up of a single body moving with constant velocity has several features that need to be discerned (for example, for a system of analysis to be treated as being in an inertial frame of reference, it needs to, inter alia, have a zero net force acting on it, and so on).

Drawing on ideas from phenomenology and Székely's (1950) study of physics students making torsion pendulum predictions, Marton and Booth (1997) introduced the idea of a person's *relevance structure* for a particular way of understanding a given phenomenon (for example, the framing of a task, or way of doing things). They defined relevance structure in terms of what is seen to be called for a given phenomenon to appropriately deal with a situation at hand (which in this paper involves students working in interactive tutorial groups on a set of assigned problems). Hence, in the context of this paper there is a critical constellation of DRAs that need to come into *focal awareness* to make up a relevance structure that is appropriate for solving a particular problem involving circular motion. These critical DRAs need to be related to one another—the "parts"—and to the "whole" simultaneously. This is because it is how these DRAs get related to each other and the whole that determines how the situations get to be seen, experienced, or understood. In this way *focal awareness*, *simultaneity* and *relevance structure* are central to VTL and thus for understanding the analysis examples given in this paper. From this perspective, when the opportunity to experience relevant dimensions of variation is limited, or if the experience of a dimension of variation is countered by a person's relevance structure of the situation, then opportunities for learning become limited for that person and vice versa. In the VTL literature such learning opportunity is characterised by the term *space of learning* (Marton & Tsui, 2004).

Here, it needs to be emphasized that the relevance structure we look at is grounded in the DRAs which physics education deem as being relevant for solving the particular kind of task that the students were working with at the time of our study. Such DRAs are taken as being self-evident for the effective teaching of circular motion, but at the same time can present a learning space limitation for individual students or groups of students. This is because for different people every situation can have a different relevance structure, which may or may not match the DRAs for the situation. Thus, the educational aim for the physics tutorials studied can be seen to be to engage the participants students in ways that lead to their collective relevance structure matching the DRAs of the physics situation(s) given in their assigned problems.

At this point, for the physics-tutorial, problem-solving, group-learning, situation that makes up the data for this article, the referral to these "dimensions of variation" needs some further situated explanation. Building on Booth and Hultén (2003) and Ingerman et al. (2009) which, for the first time, shifted the analytic focus of the *source* of variation-generation from teachers to students interacting in group work, it is the student-generated *dimensions of variation* that we are proposing to be analytically interesting for the given educational context:

> It is the individual and the individual alone that develops the capability to experience something in a new way. When speaking of the phenomenon in focus, the individual directs his or her awareness towards the phenomenon, or towards some aspect of it, or towards the situation in which the phenomenon is perceived, or towards his or her own relation with the phenomenon in a reflective mode; the locus of learning is identical with the individual learner. In group discussions, however, the locus of learning is less clear; in the transcripts of discussions utterances are directed to one another or to the collective solution that is under way rather than to oneself, and the locus of learning is distributed over the group situation – insights are jointly constituted […] What we are suggesting […] is that dimensions of variation can be opened in discussion, affording learning. This is not to say that learning takes place, neither in an individual nor in the group; but it can be said that a potential for learning is provided when a dimension of variation is opened – the conditions for learning are present to the group and to the problem-solving process. (Booth & Hultén, 2003, p. 70)

Furthermore, for the purposes of this paper, we define the space of learning for the tutorial groups of participating students to be: the possibility for learning that is afforded by the social semiotic interaction of a tutorial group for a given problem-solving task (i.e., the collective learning outcomes that arise in the given learning environment).

Thus, bringing in VTL as part of the proposed analytic framing that we explore empirically for this article facilitates identifying instances of limiting and enhancing the groups' space of learning. The simultaneous bringing in of the social semiotic analytic perspective facilitates the identification of the form and content of the semiotic systems and their resources that get used. Then, how this is analytically seen to limit or enhance the space of learning facilitates the identification of attempts to open up dimensions of variation and how these attempts get manifested in the group's interactive discussions.

In our analysis, it is the *relevance structure* construct that was mentioned earlier which has important relations to the space of learning that evolves in a tutorial group. However, since in the given analytic context it is not possible to know what the students were thinking, but only what they communicated and how they semiotically did this, we will, following Euler, Gregorcic and Linder (2020) and use the term, *enacted relevance structure*.

Part II: Data—The learning episodes

As a case study, in this second part of the paper we present our data and analysis. The data is presented in the form of two different episodes, one where students are working on a circular motion problem in the vertical plane (Section 2.1), and the other of students working with a circular motion problem in the horizontal plane (Section 2.2). The participating students are part of a first-year introductory physics class at a well-respected Swedish university (further details not given for ethical-permission reasons). At the time of the study the students had attended regular classes on circular motion, and these had included problem-solving recitations. Prior to the start of the data collection we had received ethical permission to video and audio record the discussions from all students that took part in the study.

In order to "capture" all the semiotic resources that the students made use of in their discussions, we made video recordings of each group's discussion activities while they attempted to solve the given tutorial problem. For their discussions each group was provided with large (A3) pieces of paper and given a set of coloured pens for collective working. The semiotic systems that the students typically used to communicate with one another during these tutorial sessions were, but not limited to, spoken language, gestures, diagrams and mathematics. A transcription that includes a collection of these elements is referred to in the literature as a "multimodal" transcription (for example, see Baldry & Thibault, 2006, and Bezemer & Mavers, 2011). We do likewise in this paper. In these multimodal transcripts we use **bold** letters to represent spoken emphasis and <u>underlining</u> to indicate the accompanying aspects to the emphasis. Where gestures and/or other formulations are added to the spoken emphasis they are described [*italicized in brackets*]. During our video sessions the participating students were working without any direct teacher or researcher intervention. The tutorial groups did receive short "visits" from one of the two teachers present, and this teacher would occasionally answer generalized, non-recitation type questions. However, most of the "visits" took the form of "observational visits" in that they were looking at how the groups were progressing.

In the sections below, the data is presented in the form of verbatim, multimodal transcripts. Together with each transcript we also present the analytically identified *focal awareness*, *dimensions of variation* and *relevance structure* aspects. This will be further described in the analysis section (Part III).

2.1 Episode 1: Vertical motion—"But how does it stay up?"

The first episode comes from observing a group of four students (pseudo-named as Alex, Becky, Carl and Delia) working on a vertical circular motion problem that presents a car moving with constant speed on the inside of a vertical hollow cylinder (see Fig. 1 and Appendix I for a full copy of the problem). The given task is to find the "magnitude of the normal force exerted on the car by the walls of the cylinder" in two different positions; at the bottom (marked A) and at the very top (marked B) of the cylinder (see Fig. 1). The speed of the car (constant), the radius of the cylinder, and the mass of the car were all given in the problem's description.

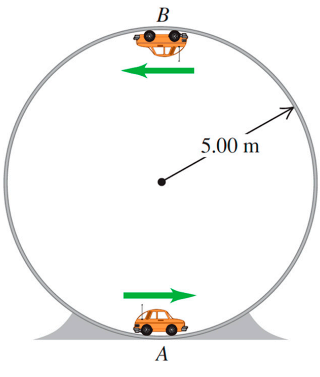


Figure 1. The given diagram for the problem in Episode 1 (Fig. E5.45, p. 187) (Young & Freedman, 2016). Reprinted by permission from Pearson Education Inc, New York, New York.

At the start of the group's discussion of how to do the given task, Alex appears to be the most confident about how to proceed, however his approach at this stage is largely numerically orientated. Becky then starts to question this approach—she is not convinced by Alex' descriptions of what forces are acting on the car at the prescribed points A and B. In an effort to create a compelling conceptualization of these forces, Becky draws a large diagram (Fig. 2) of the car in the cylinder and then uses arrows to show the forces that she sees acting on the car at the points A and B. This diagram then becomes the conceptual working document that the rest of the group uses for the rest of an emergent discussion. The thread of this emergent discussion starts with strong disagreements about what forces are acting on the car at the points in question. At this stage the group are discussing three forces, which they refer to as normal force, gravitational force, and centripetal force. However, they quickly enter into a lack-of-agreement phase with respect to the direction of the centripetal force and from where it originates. Delia proposes that there should be a force acting on the car directed upwards at the top of the loop, else the car would fall straight down. The discussion excerpt in Table 1 starts at the point when Carl proposes that the proposed upward force does not exist (i.e. doesn't act on the car).

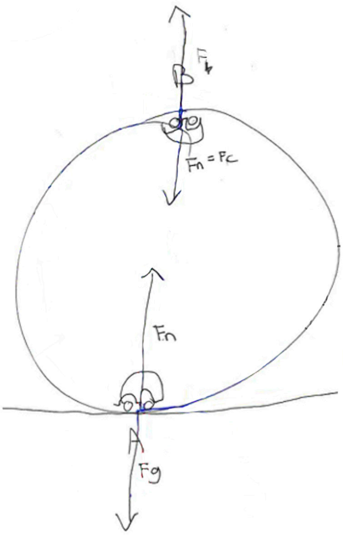
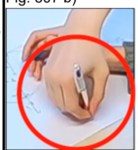
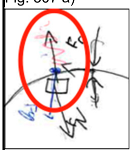
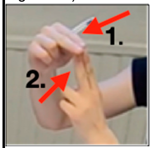
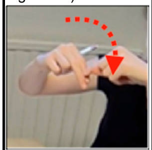
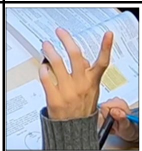
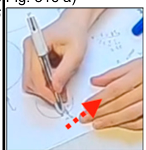
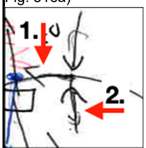
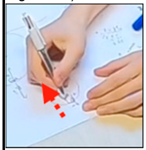
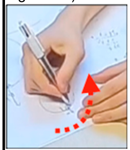
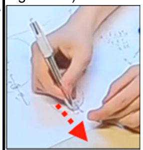
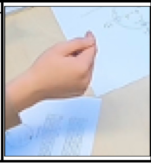


Figure 2. The diagram that Becky drew, which the group then centred their emerging discussion on.

TABLE 1. Verbatim multimodal excerpt from the first discussion between Carl and Delia.

		Multimodal transcription in different semiotic systems			**The observed relevance structure (as enacted)**	
Line ref	**Group member**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that get introduced**
307	Carl	I don't think <u>this force</u> [*the centrifugal force that Delia has drawn on the common sketch of the problem situation, Fig. 307 a)*] <u>exists.</u> [*scratches out the upward outward force sketched in acting on the car at point B from one of the used diagrams, Fig. 307 b)*]	Fig. 307 b) 	Fig. 307 a) 	The force that the track exerts on the car to get it to follow a circular path	Real and fictitious forces acting on the car
308	Alex	No, it does.			The force that the track exerts on the car to get it to follow a circular path	None
309	Becky	It does.			Experienced outward-acting forces in circular motion	None
310	Carl	It doesn't, but let me- *[interrupted by Delia]*			The force that the track exerts on the car to get it to follow a circular path	None

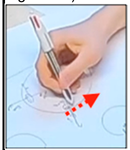
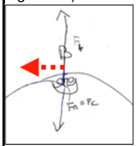
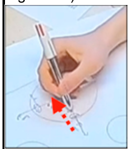
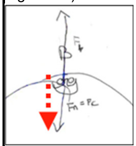
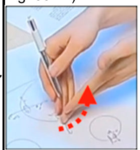
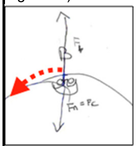
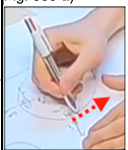
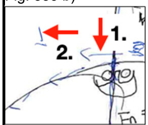
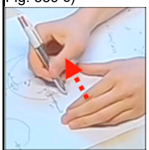
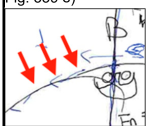
311a	Delia	But **how would it stay up** otherwise? [*looking at Carl challengingly*]			Sum of forces equals zero for a static situation	The direction of the normal force acting on the car
311b	Alex and Becky	[*looks at Delia and chuckles insecurely when she asks the question*]				
312	Carl	**Oh, because** the velocity is this way [*puts right hand fingers horizontally in the air, Fig. 312 a) nr.1*], but the acceleration this way [*adds left hand fingers vertically upwards to the other hand towards centre of the circular motion, Fig. 312 a) nr.2. The image being seemingly transposed 360 degrees was a functionality of Carl's gestured explanation*], and as the force exerts [*puts left hand fingers vertically downwards to the right hand, Fig. 312 b)*], the velocity changes like this. [*moves right and left hand simultaneously to represent the car going downwards in the circle, Fig. 312 c)*] So, there is no force going like this. [moves pen *upwards, Fig. 312 d)*] But the force acts like this- [*puts right and left-hand fingers together similar to Fig. 312b) and c,), Fig. 312 e)*]	Fig. 312 a)  Fig. 312 b)  Fig. 312 c)  Fig. 312 d)  Fig. 312 e) 		Direction of the velocity vector, acceleration vector and force vectors for an object in circular motion	Changing of the different vectors.
313	Delia	But **something** has to keep it up? [*uses index finger to point up*]			Treating the car as being in a static situation at top of the circular track	The direction of the normal force acting on the car
314	Carl	**No, no-**			N/A	N/A
315	Alex	Ahh! [*indicating that he is starting to construct a new understanding*]			N/A	N/A
316	Carl	The velocity is going like this [*draws velocity vector horizontally, Fig. 316 a) and 316 b) nr. 1*],	Fig. 316 a) 	Fig. 316a) 	Changing velocity and force that car exerts on the car and these are responsible for the circular motion	Changing direction of velocity

		but then the force goes like this, [*draws force vertically downwards from the top, Fig. 316 c) and b) nr.2*] which makes it change. [*gestures with pen the circular path, Fig. 316 d)*]	Fig. 316 c)  Fig. 316 d) 			
317	Delia	But- [*Interrupted by Carl from going back to her question of what would stop the car from falling down*]			What would happen to a static car in this position?	The direction of the normal force acting on the car
318	Carl	But there is no force [acting on the car] going like this [outwards]. [*uses pen to gesture force vertically upwards on top of diagram, Fig. 318 a) and b)*]	Fig. 318 a) 	Fig. 318 b) 	Normal force acting on the track is not a force acting on the car	Forces acting on the car in terms of what is real and what is fictional
319	Alex	It's the other way. [*uses index finger to gesture the direction of the force acting on the car*]			Car pushes on track outwards and in return the track pushes on the car inwards	Newton III pairs of forces.

In this section of the discussion Carl opens up the possibility that the suggested upward force acting on the car at point B does not exist (implying that it is a fictitious force, Line 307). At this stage in the conversation, neither Becky, Delia nor Alex, agree with him; they remain convinced that the car needed a force to prevent it from falling straight down—"something has to keep it up" (see Lines 311 and 313). However, Alex is starting to show signs of giving serious thought to Carls explanation following his opening up of new dimensions of variation (see Line 312), i.e., starting to incorporate new DRA's into his relevance structure. The dimensions of variation that Carl opens up are underpinned by a shifting from a static thinking stance to a dynamic thinking stance vis-à-vis an inertial reference frame point of view. Carl does this by drawing on the gesture semiotic system to use semiotic resources made up of two sliding arms, each with two finger aligners (see the Gesture column under Lines 312, 316 and 319). We characterize this as a "gesture-based unpacking" of the physics relationships that Carl sees between the instantaneous velocity of the car, the corresponding acceleration, and the specifying of the net force responsible for that acceleration. To do this, Carl generated variation within the DRAs, thus opening up the corresponding dimensions of variation.

Right after the discussion part given in Table 1, one of the teachers who were present during this activity approached the group and, after being asked, confirmed Carl's case regarding the non-existent force—the fictitious outward acting force—the upward force acting on the car at the problem-given point B. Both the teacher and Carl clarified what they meant by the "force doesn't exist" by stating that there is no upward force acting on the car at point B. However, this is *transcended by the group*, which is taken on by Delia who again asks how the car could stay up otherwise (Table 2, Line 336). In the Table 2 piece of the discussion, Delia and Carl continue debating the upward force. Carl (Lines 337 and 339) tries to once again demonstrate to Delia how the velocity, acceleration and force are related with respect to having the car follow a circular path. Carl does this by opening up a dimension of variation based upon the direction of the relevant velocity vector. He does this using gestures and sketches as illustrated in Table 2. Even though, finally, in Line 340, Delia indicates that this aspect is now in her focal awareness, she does not go on to try and have this aspect become part of the group's relevance structure. Thus, we have taken her response in Line 340 to be seen to be wanting to agree with the teacher, and the aspect remained transcended for her.

TABLE 2. Verbatim multimodal excerpt from the second discussion between Carl and Delia.

		Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
Line ref	**Group member**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcript**	**Dimensions of variation that gets introduced**
336	Delia	But how does it stay up? [*looks at the teacher*]			What would happen to a static car in this position?	The direction of the normal force acting on the car
337	Carl	[Answering for the teacher] Because, the velocity is going **this way** [*moves pen along velocity tangentially on top of the diagram, Fig. 337 a) and b)*],	Fig. 337 a) 	Fig. 337 b) 	Velocity vector and how it changes and how the force that the track exerts on the car is responsible for the continuous changing in velocity	Variation of the direction of velocity and simultaneously of the force that the wall exerts on the car.
		and the force is going this way [*gestures the direction of the force downward towards the centre of rotation, Fig. 337 c) and d)*]	Fig. 337 c) 	Fig. 337 d) 		
		which makes the **velocity vector change**. [*puts hands together with the fingers continuously changing direction as he aligns them along the changing displacement that makes up the circular path, Fig. 337 e) and f)*]	Fig. 337 e) 	Fig. 337 f) 		
338	Delia	Yeah? [*incredulous questioning to Carl and teacher*]			N/A	N/A
339	Carl	[Attempting to have the dimension of variation that he opened become more discernable to Delia and the rest of the group] But it [*the car*] stays up because it's going like this [*draws velocity vector arrow tangential to the loop, Fig. 339 a) and b) nr. 1*],	Fig. 339 a) 	Fig. 339 b) 	Velocity vector and how it changes and how the force that the track exerts on the car is responsible for the continuous changing in velocity	Variation of the direction of velocity vector as a function of the movement of the car in a circle
		but the force goes like **this** [*draws force arrow directed downward, Fig. 339 c) and b) nr. 2*)],	Fig. 339 c) 			
		which makes it change like this- changes like this, and so on [*draws how the velocity vector changes, Fig. 339 d) and e)*]. It changes- the vector changes, but not-	Fig. 339 d) 	Fig. 339 e) 		
340	Delia	Oh, okay. I see.				

This outcome leads to the question of why VTL does not seem to be opening up the space of learning for the group? What our analysis suggests is that there are two essential things missing into the group interaction; (1) a readiness to take on what became discernable with the new experiences of dimensions of variation that were introduced by Carl into the group and individuals' relevance structure for the given problem; and (2) what is referred to as *Diachronic simultaneity* and *Synchronic simultaneity* in VTL. A short discussion of these two constructs thus follows.

2.1.1 Simultaneity re-visited

Earlier, in the section that introduced the essential features of variation, simultaneity was characterized as an essential part of the learning process as follows: the once *transcended* or *taken-for-granted* must be simultaneously seen with the *no-longer-transcended* or the *no-longer-taken-for granted* for a dimension of variation to be opened around some important disciplinary aspect. In this section a more fine-grained discussion is given.

Having something brought into one's focal awareness is an important step towards enhancing one's relevance structure. But this may not be sufficient to learn something new. Complex phenomena need several "pieces" of focal awareness to be brought together simultaneously for the constitution of new meaning. In VTL this dynamic has two threads (Marton & Tsui, 2004). The first is referred to as *Diachronic simultaneity*. This kind of experienced simultaneity is characterized by a bringing together of aspects of a phenomenon that have been experienced before together with what is currently being experienced. In this way, variation in the experience of the phenomenon gets to be experienced. This is how things get compared. For example, the differentiation of live versions of the famous opera masterpiece "Flower Duet" from "Lakmé" derive from many diachronically simultaneous aspects, for example, the venue, where one might be sitting in that venue, the singer, the orchestra, the conductor, and so on. Learning to distinguish between the different types of species of hyena—the spotted hyena, the striped hyena, the brown hyena and the aardwolf—one would need to start by knowing the specific aspects of at least one of the species and then experience diachronic simultaneity to be able to give distinguishing consideration to another of the species.

Then there is the experience of *Synchronic simultaneity.* This kind of experienced simultaneity is characterized by a bringing together of discerned aspects of a phenomenon that are considered to be needed when critical aspects are brought together at the same time (meaning discerned and focused on at the same time). For example, suppose that a spotted hyena and a striped hyena are presented together in photographic form. To make a definitive differentiation, the dimensions of variation of size, length of body hair, and markings on the body will need to be opened simultaneously.

In physics we have the possibility of describing light in terms of a wave. We also have the possibility of doing this in terms of particles (photons). Experiencing these two aspects with both diachronic and synchronic simultaneity is arguably what allowed Einstein and Infeld (1938, p. 278) to observe the following: *"It seems as though we must use sometimes the one theory and sometimes the other, while at times we may use either. We are faced with a new kind of difficulty. We have two contradictory pictures of reality; separately neither of them fully explains the phenomena of light, but together they do."* This is not to imply that the outcomes of such simultaneous experiencing leads to a fixed outcome. When Feynman discerned these different dimensions of light with both diachronic and synchronic simultaneity this arguably facilitated the underpinning parts of his invention of quantum electrodynamics: *"Newton thought that light was made up of particles-he called them 'corpuscles' and he was right (but the reasoning he used to come to that decision was erroneous). [...] light is something like raindrops—each little lump of light is called a photon—and if the light is all one color, all the "raindrops" are the same size. [...] I want to emphasize that light comes in this form— particles. It is very important to know that light behaves like particles, especially for those of you who have gone to school, where you were probably told something about light behaving like waves. I'm telling you the way that it does behave—like particles."* (Feynman, 1985, pp. 14–15).

Mok et al. (2002) and Tsui (2002) have illustrated how the order in which variation is introduced affects what is simultaneously in focal awareness. This could also be a factor in the sequence of events in the given data episode, but it would be extremely challenging analytically to "pull off" a "staging" of the ordering of the dimensions of variation that get introduced in such tutorial group discussion for empirical analysis.

2.1.2 Summary of Episode 1

In Episode 1 the students can be seen to be struggling to find a common relevance structure that includes a common perception of what forces acting on the car are relevant for correctly solving the tutorial problem (in this episode, at point B at the top of the circular loop). Delia is arguing for an upward force to keep the car from falling inwards, which is initially supported by Alex and Becky. At the same time Carl opens up dimensions of variation to help Delia get to see how the velocity, acceleration and force from the wall acting on the car at this point are related, and in so doing wanting her to see why there is no such upward force that is relevant for correctly solving the problem—in his words, it does not "exist". To be able to share this part of his relevance structure, Carl uses gestures (in addition to the diagram and spoken language) to open up these dimensions of variation. This is an example of how gestures and sketches can be used to generate *dynamic* dimensions of variation that call for experiences of Synchronic simultaneity to foster understanding (which the analysis suggests does not occur for the rest of the students during this episode).

In this episode Carl generates three different, but interconnected, dimensions of variation, namely the direction of the velocity, acceleration and force from the wall acting on the car. From the discussion that makes up the Episode our analysis suggests that Delia is not able to see how the changing velocity of the car is related to specifying the forces acting on the car, i.e., this aspect is transcended to her and she has no experience of Synchronic simultaneity. This suggests that her class engagement with what was presented about circular motion did not generate any experiences of Diachronic simultaneity. Analytically this is why the changing velocity of the car is seen not to form part of the rest of the student's enacted relevance structure during the discussion that makes up Episode 1. Having this insight into the learning challenge presents teachers with their own challenges—discernment of the DRAs for a particular physics situation is necessary, but that is not enough. Creating appropriate experiences of simultaneity is also needed, and our position here is that the optimal way of doing this is by evoking variation scenarios using different semiotic-system resources—resources that are more easily used to constitute discerned DRAs—what are initially being experienced by students as quasi-independent pieces become emergent, context specific, coherently connected "wholes".

2.2 Episode 2: Horizontal motion—"What stops you from getting pushed in?"

The second episode involves horizontal circular motion and comes from another group of four students (pseudo-named Eric, Frank, Gloria and Holly) who are working on a problem involving a horizontal "swing ride" (see Fig. 3). This problem (see Appendix II for a full copy of the problem) includes a part that asks "what forces act on a rider with mass m".

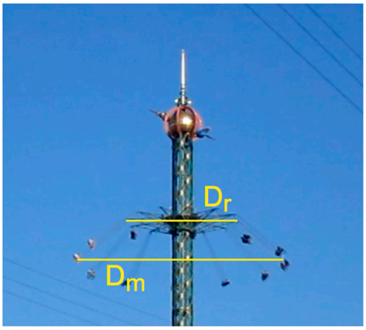


Figure 3. The figure to the problem given to the students in Episode 2. The photo shows the swing ride *Himmelskibet* at Tivoli, Copenhagen. This figure is reproduced from Pendrill (2016, p. 4) under CC-BY 3.0 license.

In Episode 2, the students are discussing whether there needs to be an outward force acting on the person on the swing (the rider) to get and keep the swing elevated into a circular orbit. Gloria consistently argues for such an outward force while Frank strongly disagrees with the proposal. Gloria and Frank thus lead the discussion. From the beginning, Gloria and Eric agree that there is a tension force, a gravitational force, and an acceleration that is "pulling it inwards". However, Gloria returns to what is in her relevance structure, which is that there needs to be an outward force acting on the rider—a force that acts in the opposite direction to what she refers to as an inward acting "acceleration force" (marked F_a in Fig. 4a). Gloria illustrates her argument using a sketch—a free body diagram of the rider showing the forces acting on the rider—which she then presents to the other students (Fig. 4a). At this point in the discussion, Frank who does not have such a force in his relevance structure (see Fig. 4b) declares it to be "not even *a force*" (Table 4, Line 206). At this point our analysis is that Frank is experiencing Diachronic simultaneity of what he has experienced in everyday life and what he has learned in his physics classes—this can be seen in his justification for the outward force not even being a force: “It’s just created because of the third **Newton’s law**: *for every force there is a [unclear] force in opposite direction*”*,* which is “transduced” into gestures using an inward and outward spreading of his hands.

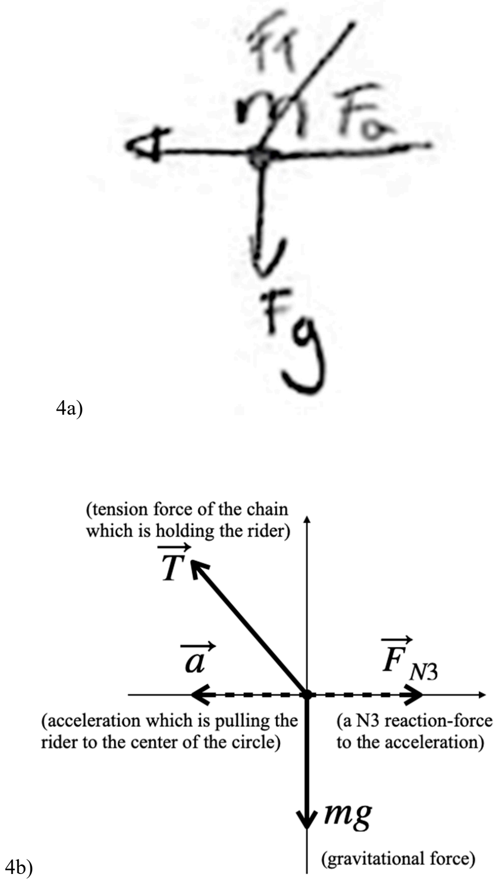
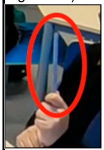
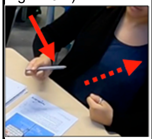
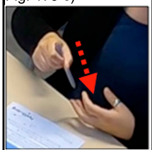
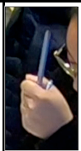
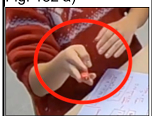
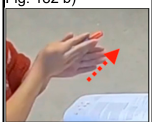
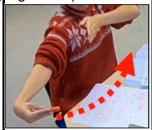
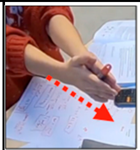


Figure 4 Gloria's free body diagram representing her relevance structure (a) made at the time of discussion that began in line 179, and an illustrated version of the enacted relevance structure of Frank (b). Note that 4b) is drawn from Franks perspective and illustrates how he views the swing and rider being in the right-most point of the horizontal circle.

TABLE 3. Verbatim multimodal excerpt from the first discussion between Frank and Gloria.

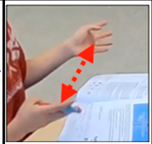
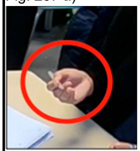
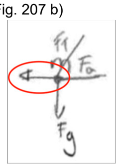
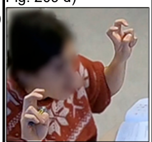
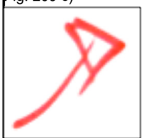
		Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
Line ref	**Group member**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcripts**	**Dimensions of variation that gets introduced**
179	Gloria	At the moment the tension force is holding it, [*places pen vertically upwards, Fig. 179 a)*] the acceleration is pulling it inwards, [*places pen horizontally and moves body as being "pulled inwards", Fig. 179 b)*] and your gravitational force is pulling you down, so you don't fly up. [*moves pen vertically upwards, Fig. 179 c)*] But what stops you from getting, like, **pushed in**?	Fig. 179 a)  Fig. 179 b)  Fig. 179 c) 		Tentative frame of reference. Tension force, centripetal acceleration, gravitational force, velocity.	No variation, just identification of forces.
180	Frank	Pushed in? [*looks at Gloria*]			What force could be pushing upward here?	The possible pushing and pulling forces acting on the rider
181	Gloria	Yeah [...] You have the tension force which is holding [it]- [*places pen vertically upwards*]			Tension force	Direction of the tension force
182	Frank	No, **your velocity** is [*places right hand vertically "forward" to indicate an instantaneous tangential direction, Fig. 182 a)*] keeping you from going [*puts hands together to represent two opposing forces, Fig. 182 b)*] inside.	Fig. 182 a)  Fig. 182 b) 		Instantaneous velocity vector,	Continuously changing direction of the velocity vector
183	Gloria	Yeah. [*looks at Frank*]			Seemingly the same as Frank	Seemingly the same as Frank

184	Frank	And the **rope**, what it's doing is like, keeping you in a circle. [*makes a right angle with his right hand and arm and moves in a semi-circular path, Fig. 184 a)*] But there is no force going- pushing you inside. [*gestures with right hand how the rider should not be seen as being "pushed inside", Fig. 184 b)*]	Fig. 184 a)  Fig. 184 b) 		Tension force in the rope and non-existing "inward pushing" force	Changing direction of tension force provided by the rope. No pushing inside force just a force to change the direction of the instantaneous velocity.
185	Gloria	But how are you then not **sucked in**? [*peers at Frank questionably*]			Acceleration being directed towards centre of circle assumes a force acting in that direction -- a "sucking in" force. And this force needs to be counter balanced if the rider is to continue with circular motion.	Pushing and pulling forces acting on the rider.
186	Frank	Because your velocity is always tangential. [*puts both hands together and moves them horizontally forward*]			Tangential velocity vector	Direction of velocity vector
187	Gloria	Yeah, yeah-			Seemingly the same as Frank	Seemingly the same as Frank

Earlier the analysis presented for Episode 1 illustrated how spoken language was enabled by different physical movements and gestures to open up dimensions of variation for background elements that are not in the relevance structure for the task at hand. In contrast, the analysis presented in Table 3 for Episode 2 illustrates how spoken language is enabled by different physical movements and gestures to open up dimensions of variation for the taken-for-granted in ways that are directed towards seeing things in a new way; a no-longer-taken-for-granted way. The dimension of variation being discussed are the push and pull forces acting on a rider experiencing circular motion while on an amusement park swing ride such as shown in Fig. 3. The taken-for-granted is an outward acting force. Here, in particular, Gloria and Frank's opening of new dimensions of variation manages to shift the taken-for-granted to a no-longer-taken for granted. And there is evidence that right at the end Gloria is getting increasingly primed to enter into an emergent phase of getting to see the constructs of centripetal and centrifugal forces in a new light. Frank, on the other hand, in this episode can be seen to be strongly situated in this emergent phase of learning. In relation to relevance structure for this episode, we characterize Frank as having a dynamic relevance structure and Gloria as a static one. This gets played out as follows: Gloria presents her ideas of what forces are acting on the rider, which include a set of inward and outward acting forces (see her free-body diagram in Fig. 4a). Frank is strongly opposed to taking such forces into account and argues that it is the velocity of the swing that keeps the rider from being drawn to the centre of the circle. His opening up of a new dimension of variation for his argument does not convince Gloria that there needs to be a force to prevent the rider from being "sucked in" (line 185) towards the centre of circular motion. Frank then uses sketches to bring focal awareness to the instantaneously changing velocity vector and how this translates into an acceleration that is directed towards the centre of the circular motion.

Towards the end of Episode 2 (see Table 4, Line 205) Holly re-introduces the idea that an outward force is needed to counter the inward pulling tension force of the swing chord. Frank immediately challenges this by declaring it "not even a force" just a consequence of Newton's third law. But Holly's proposal is authoritatively supported by Gloria who establishes her authority from what she "learned in school" before declaring that an outward force is needed to prevent the swing from getting "sucked in".

TABLE 4. Verbatim multimodal excerpt from the second discussion between Frank and Gloria.

		Multimodal transcription in different semiotic systems			The observed relevance structure (as enacted)	
Line ref	**Group member**	**Spoken language**	**Gestures**	**Diagrams and sketches**	**Focal awareness seen in the transcripts**	**Dimensions of variation that gets introduced**
205	Holly	**It is** always another force. [*looks at Frank*]			What is responsible for making the rider here follow a circular path?	Forces that are not apparent
206	Frank	It's not even **a force**. It's just created because of the third **Newton's law**. For every force there is a [unclear] force in opposite direction. [*move hands back and forth*]				N3 forces are "not real forces" – just reactions to the real force
207	Gloria	So, okay so for me- because I **learned it in school**, you draw the other side [force] too. [*points pen in direction of "other side" indicating a centrifugal force, Fig. 207 a) and b)*] And that just makes sense because otherwise that looks as you are- yeah, you **get sucked** in. But because I am not allowed to draw a velocity force at the moment-	Fig. 207 a) 	Fig. 207 b) 	All forces acting on the rider, and in particular the fictitious N3 orce outwards, which is later in the xplanation referred to as being the centrifugal force	Variation in the direction of the centrifugal force
208	Eric	Okay-			Seemingly the same as Frank	Seemingly the same as Frank
209	Frank	Because you- if you don't draw the tangential velocity. [*draws a pictorial arrow to oven up another tangential velocity dimension of variation, Fig. 209 a) and b)*] You have to draw like this, sketching *an inward facing arrow, Fig. 209c)*] **centrifugal** force. [*makes quotations marks in the air*, Fig. 209 d)]	Fig. 209 a)  Fig. 209 d) 	Fig. 209 b)  Fig. 209 c) 	Velocity vector's direction in relation to the direction of the centrifugal force	Variation of centrifugal force outwards (a N3 force and thus "not even a force")

2.2.1 Summary of Episode 2

During the discussion piece transcribed in Table 4 Frank goes on to again try to get Gloria to appreciate the changing direction of the speed of the swing-rider as they move in a circular path. However, Gloria is committed to a static relevance structure and thus, discerning only what is taken-for-granted—that there has to be an outward facing centrifugal force (e.g., see Line 207). Although Frank has repeatedly presented a no-longer-taken-for-granted scenario, his associated dimensions of variation have not opened for the rest of the group—the dynamic of seeing both the taken-for-granted and no-longer-taken-for-granted simultaneously, does not materialize. Booth and Hultén (2003, pp. 69–70) explain this as follows:

> "Simultaneity" – seeing both the once-taken-for-granted and the no-longer-taken-for-granted – is demanded for the dimension of variation to open. Lack of understanding is thus linked with being unaware of the potential for variation – seeing only that which is taken-for-granted.

So, while the discussion revolves around the need for an outward force acting on the person on the swing, this outward force is proposed to be necessary to prevent the swing from being drawn to the centre of the circle by the force responsible for the (centripetal) acceleration that is directed towards the centre of the circular motion. On the other hand, Frank is convinced that this is not a real force, but a reaction force arising out of Newton's third law (N3). And even though he draws attention to some relevant physics by opening up a new dimension of variation of the direction of the velocity, because of the static nature of the relevance structures of his peers they get no access to the dimension of variation that Franks attempts to open for them.

Part III: Discussion

3.1 Arising analytic considerations

Our aim in this paper was to illustrate empirically how the semiotically enhanced variation theory perspective can be used as an analytical tool to better understand learning challenges in physics in a way that can inform and improving the educational experience. When some aspect is presented in one semiotic system (say mathematics) and reformulated in that system, that is referred to in the literature as *transformation*. When it is presented in one system (say spoken language) and reformulated for presentation in another system (say gestures) that is referred to in the literature as *transduction* (see Bezemer & Kress, 2008; Kress, 2010; as well as, Volkwyn et al., 2019; and, Volkwyn, Gregorcic, Airey, & Linder, 2020, for physics discussion and illustration). What is seen in the multimodal transcriptions of our episodes are transductions of spoken language and mathematics into gesture and sketch, and then having these semiotic parts supplement one another in the communication practice. Hence, we began our analysis by identifying communicative episodes in the data sets that brought to the fore well-known learning challenges (Section 3.1.1). Using multimodal transcriptions that semiotically enhanced the identification of key variation constructs we then showed how these constructs had the possibility to generate analysis and insight not seen in this way before. In particular, we illustrated not only necessary conditions for learning, but what was needed to have those conditions work educationally.

The variation perspective has for many years now offered both teachers and researchers a theoretical and practice framework for approaching learning and the addition of a social semiotic perspective has already been posited as an enhancing of this framework. The analysis presented here is intended to show that empirically. In particular, specific aspects of physics learning call for a relevance structure made up of context-specific DRAs. And since one of the basic grounding aspects of variation theory is that knowledge is characterized in terms of being a relation between the knower and known, any changes to a person's relevance structure reflect a change, *a qualitative change*, in the relevance structure. And the emergence of such changes become observable through communicative action across semiotic-resource systems.

3.1.1 Identification of communicative sequences

The method of analysis that we illustrate began with the identification of educationally interesting threads of students group communication during physics problem-solving tutorials. These were then placed into episodic pieces (see Tables 1-4). The pieces were analysed first individually and then collectively by the authors in order to fulfil trustworthiness of the study (internal validity and reliability control). We used a combination of social semiotics and variation theory to create an analytic approach that looked at the way the students were communicating rather than only what they were communicating.[1]

In the illustrative episode pieces, the way the students communicated amongst one another in their tutorial groups was built on identifying what the relevant forces were that acted on the object of interest (car in the first case and swing rider in the second), and what the direction of these forces was using both explicit and

[1] Indeed, our focus in this paper is on the analysis rather than on the physics concepts and knowledge by the students. An in-depth analysis of the physics aspects will be presented elsewhere (Eriksson et al., in preparation).

implied coordinate systems. The most critical identified DRAs for the students in Episode 1 included velocity, acceleration, and the force from the wall acting on the car. For the students in Episode 2, the most critical DRAs were identified to be the velocity and the tension force. The identification of these sequences was made possible by paying attention to the DRAs that the students were discussing. However, since the DRAs of this problem are identified from the discipline's perspective, the aspects that students chose to consider may or may not overlap with these disciplinary aspects. The observed parts of the collective enacted relevance structure that matched DRAs consisted of the following components: the system, radius, mass, normal force, tension force, gravitational force, centripetal force, centripetal acceleration and instantaneous velocity.[2]

3.1.2 Students' *enacted* relevance structure

The next step in our analysis was to use our analytical framework to figure out what the multimodal transcripts could analytically reveal about interactive group learning for the given tutorial problems. In other words, we had to determine what the students communicated and what they intend to communicate in the chosen discussion episodes and tease these apart. As discussed earlier (Section 1.2), a person's *relevance structure* is what a person finds to be relevant, what matters in a particular situation, in this illustrative case, solving a particular physics problem. Our empirical approach used an analytic tool that linked the students' positioning with their peers—*enacted relevance structure.* Two clear examples of this *enacted relevance structure* "in action" that were provided in the data presented earlier were Delia constantly arguing that there needs to be something to stop the car falling down when it is at the top part of the circular loop given in the tutorial problem, and Gloria suggesting that there should be a force directed outwards on the swing to prevent it from being "sucked in" and when she goes on to say that she is "not allowed to draw a velocity force at the moment".

Once the enacted relevance structures of individual students had been identified, we then sought to understand more about the what learning possibilities were emerging from the group's interactive communication. For example, in Episode 1, Carl wanted Delia to see to the connection between the change in velocity and the force that the wall was exerting on the car—"Because, the velocity is this way, and the force is going this way which makes the velocity vector change." And Frank, in the swing problem, wanted Gloria to get to see the connection between the change in velocity and the tension force of the chain—"No, your velocity is keeping you from going inside. [...] And the rope, what it's doing is like, keeping you in a circle."

3.1.3 Variation and dimensions of variation

Having been able to identify students' individual enacted relevance structures and noticing that the students were intending to change their peers' relevance structure, the next step in our analysis was to understand more about <u>how</u> the students were doing this. What mechanisms and tools were they using to try to make this possible? This means that we looked more closely into the ways in which students' relevance structure diverged from their peers' and how they tried to make their relevance structures converge by offering spontaneous variation around a certain important aspect of the problem.

To gain this understanding we analysed the communication from a variation theory perspective while looking at the chosen sequences when they were trying to convince each other to change their relevance structure. Using this perspective, we were able to identify a structured, but spontaneous, variation in important aspects of the problem. Following the theoretical ideas presented earlier (Section 1.2), variation theory states that one needs to experience difference against a background of sameness to be able to discern a new aspect. This is how we interpret the students' communication while giving reasons or evidence in support of an idea with the aim of persuading others to share one's view. One example (Table 3 and 4) is how Carl wanted Delia to focus on the velocity and thus created a dimension of variation around this aspect—which represents different *values* of this dimension, in this case how the direction of the velocity vector changes to give rise to a centripetal acceleration.

One dimension of variation in particular, which we were able to identify that the students used in their discussions, was the *direction of the velocity vector*. Both Carl (Table 1 and 2) and Frank (Table 3 and 4) brought up this dimension of variation while trying to respond to Delia and Gloria's proposals regarding the force situation for the car and the swing, respectively. Further, they are essentially attempting to open a

[2] We use the term "components" because what emerged was a series of descriptions that were not always fully compatible in the sense that different students presented what could only be characterized as DRA subsets.

dimension of variation when presenting different values of this aspect. However, from the analysis we see that this variation in itself may not be enough for the students to change their thinking if they cannot discern the DRAs.

How did the students offer this variation to their peers? Carl used gestures (see Table 1, line 312, and Table 2, line 337) in addition to spoken language and diagrams. We suggest that the use of gestures could offer different possibilities for discerning the critical aspects of the problem, compared to what the diagrams and spoken language alone could. Similarly, for the swing problem, Frank also made use of additional gestures (see Table 3, line 182-186) when trying to convey his message to Gloria. In both cases, the changing direction of the velocity represents different values of the dimension of variation for the velocity.

3.1.4 A brief note on relevance structure as an analytic construct

Students' relevance structures for physics phenomena, parts of phenomena, problems to be solved etc., can be related to the PER resources perspective (for an overview, see Redish, 2003, 2014), however exploring this further requires a discussion that reaches beyond the realms of this paper beyond saying that the epistemic grounding for the PER resources perspective and that of relevance structure are quite different—relevance structure is derived from the anatomy of awareness perspective drawn from phenomenology and phenomenography, whereas the PER resource perspective has its epistemic roots in discourse analysis (one of the principal roots being Tannen, 1993).

3.2 Arising considerations for teaching

There have been previously described approaches to improving physics learning outcomes through the use of variation theory (for example, Fraser & Linder, 2009; Fredlund, Airey, et al., 2015; Linder & Fraser, 2009; and Linder, Fraser, & Pang, 2006). These studies have shown how design-structured experiences of variation can be considered to be a key ingredient to enhance the possibilities for student learning. In our illustrative analysis the explicit inclusion of giving consideration to the resources of semiotic systems (be it through semiotic transformation and/or transduction) brings the possibility of new understanding of learning challenges in physics when taking into account relevance structure, the opening up of new dimensions of variation, and gaining "access" to these new dimensions of variation—being able to experience them for discernment.

Being able to identify instances of limiting and enhancing a group's space of learning in terms of the DRAs that form part of the intended object of learning and students' observed enacted relevance structure, offers new design tools to teachers wanting to enhance learning outcomes. Since the educational focus for us is physics, the discernment referred to here is best characterized as *disciplinary discernment*—"noticing something, reflecting on it, and constructing meaning from a disciplinary perspective" (Eriksson, Linder, Airey, & Redfors, 2014, p. 170).

We suggest that one way of understanding the role that a person's relevance structure has for their ability to experience disciplinary discernment has two factors. First there is the role of experienced *simultaneity* as described earlier. Without such simultaneity the discernment of transcended or taken-for-granted DRAs is theoretically not possible. This is the situation even when a person has a new dimension of variation opened for them (as confirmed in the earlier given citation of Booth & Hultén, 2003, p. 69). The second factor that we are proposing is one of *epistemological commitment*—where a person is committed to a particular relevance structure from intuitive and experiential interpretations of a phenomenon (or part of it). Since there is little agreement on the meaning or definition of the construct of ''epistemological beliefs'' in the literature, we need to provide what we mean by the term, which is: *epistemological commitment is about the commitment to a particular way of thinking about something. It's about deciding whether to notice something new in a meaningful way when one is given the possibility to do so—when that new meaning making does not well match a belief, understanding, meaning that has already been constituted*. For example, in the transcribed discussion given in Table 3 (Lines 179-187), Gloria's epistemological commitment to a centrifugal (outward facing) force acting on an object following a circular motion path is very evident. And it appears to be a contributing factor to Gloria not accessing the dimensions of variation that Frank was attempting to open for her to counter that understanding. How does this work with the variation-theory needed simultaneity? We propose that such epistemological commitments prevented the variation-theory needed simultaneity from emerging—thus preventing learning from taking place. Hence, our illustrative analysis has revealed a critically important aspect for variation theory to address—what is needed from an anatomy of awareness standpoint to promote a change in epistemological commitment that is preventing the needed experience of simultaneity?

Part IV: In conclusion

In this paper we have illustrated how to apply and link a social semiotic analysis to a variation theory analysis. This facilitated the identification and interpretation of student's enacted relevance structure for specific sequences of interactive discussion as a function of physics tutorial group work. We also illustrated how to combine variation theory and social semiotics to analytically explore the opening (or not) of different dimensions of variation for group participants. The ensuing insights from this case study suggest that such combinations of social semiotics and variation theory facilitate a new level of understanding of learning challenges in physics while at the same time offering new design principles for teachers to use to enhance learning outcomes. At the same time, the analytical constructs introduced have great potential for enhancing teachers' understanding of their students' learning.

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Appendix I

The full problem used in Episode1: Exercise 5.45, with Figure E 5.45, p.187 (Young & Freedman, 2016).

> A small remote-controlled car with mass 1.60 kg moves at a constant speed of $v = 12.0\ m/s$ in a track formed by a vertical circle inside a hollow metal cylinder that has a radius of 5.00 m (**Fig. E5.45**). What is the magnitude of the normal force exerted on the car by the walls of the cylinder at (a) point A (bottom of the track) and (b) point B (top of the track)? (Young & Freedman, 2016, p. 187)

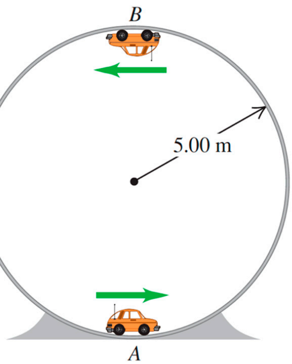

Figure 1. Figure E5.45 (Young & Freedman, 2016, p. 187).

Appendix II

The full problem used in Episode 2.

> This photo shows the Himmelskibet ("Star flyer") ride visible from Copenhagen Hovedbanegård. The diameter at rest is 14 m and the chain length is 8 m. From the photo, the ratio between the diameters at motion and at rest can be estimated to 1.9.
>
> 1. What is the angle between the chains and the vertical?
> 2. If the ride makes a full turn in 6.3 s, what is the speed of the rider in the swing?
> 3. What is the acceleration of the rider?
> 4. What forces act on a rider with mass *m*? Draw a free-body diagram
> 5. How could you use the photo to estimate the acceleration? Compare the value to your result in 3.

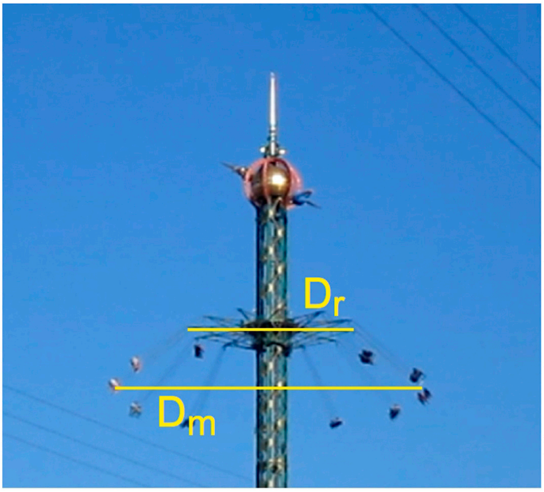

Figure 2. This figure is reproduced from Pendrill (2016, p. 4) under CC-BY 3.0 license.