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Learning Physics through Transduction

A Social Semiotic Approach

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Abstract

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This doctoral thesis details the introduction of the theoretical distinction between *transformation* and *transduction* to Physics Education Research. Transformation refers to the movement of meaning between semiotic resources within the same semiotic system (e.g. between one graph and another), whilst the term transduction refers to the movement of meaning between different semiotic systems (e.g. diagram to graph). A starting point for the thesis was that transductions are potentially more powerful in learning situations than transformations, and because of this transduction became the focus of this thesis. The thesis adopts a *social semiotic approach*. In its most basic form, social semiotics is the study of how different social groups create and maintain their own specialized forms of meaning making. In physics education then, social semiotics is interested in the range of different representations used in physics, their disciplinary meaning, and how these meanings may be learned. Students need to gain *representational competence* in interpreting and using the different representations they meet in their physics education and this thesis examines how this might be achieved. Empirically, the thesis investigated *interactive engagement* through the use of *probeware*. Such approaches have been shown to promote learning, although the reasons why this occurs are less well understood. The above matters are given consideration in three case studies that investigate the collaborative learning of introductory physics students' when using a particular probeware tool, the *Interactive Online Laboratory System* or iOLab. The thesis presents two central findings. First, probeware tools are found to be particularly effective in teaching and learning of disciplinary content when they combine high *pedagogical affordance* with high *disciplinary affordance* with respect to the intended learning goals. Second, transduction is shown to be central to teaching and learning physics in the case study setting of student laboratory work. This is because the movement *between* semiotic systems helps create the variation necessary for students to notice disciplinary relevant aspects. Moreover, the results suggest that physics lecturers should pay particular attention to students' personal transductions as these provide insights into what, and how learning is taking place. The thesis suggests that introductory level physics students will initially view coordinate systems as fixed in a standard up-down orientation. The analysis demonstrates how students can come to appreciate the movability of coordinate systems without the need for mathematical calculations. It also suggests that part of the reason that interactive engagement is effective is because it requires communication about physics conceptualisations with peers. Finally, the thesis proposes a refined definition of representational competence and suggests how such representational competence can be effectively developed. The implications of the research findings for the teaching and learning of physics are discussed and suggestions for future work are presented.

Keywords: Introductory physics, transduction, interactive engagement, social semiotics, representational competence, probeware, mathematical tools, 1-D kinematics, coordinate systems, magnetic field, pedagogical affordance, disciplinary affordance

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To my parents and family in the Lord Jesus Christ

List of Papers and supporting work

Papers

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

I. Volkwyn, T. S., Airey, J., Gregorcic, B., Heijkensköld, F., & Linder, C. (2018). Physics students learning about abstract mathematical tools when engaging with "invisible" phenomena. In L. Ding, A. Traxler, & Y. Cao (Eds.), *2017 Physics Education Research Conference Proceedings* (pp. 408–411). American Association of Physics Teachers. https://doi.org/10.1119/perc.2017.pr.097

II. Volkwyn, T. S., Gregorcic, B., Airey, J., & Linder, C. (2020). Learning to use Cartesian coordinate systems to solve physics problems: the case of 'movability.' *European Journal of Physics*, *41*(4), 045701. https://doi.org/10.1088/1361-6404/ab8b54

III. Volkwyn, T. S., Airey, J., Gregorcic, B., & Heijkenskjöld, F. (2019). Transduction and Science Learning: Multimodality in the Physics Laboratory. *Designs for Learning*, *11*(1), 16–29. https://doi.org/10.16993/dfl.118

IV. Volkwyn, T. S., Airey, J., Gregorcic, B., Linder, C. (manuscript in preparation, 2020). Can students' mathematical expectations present a barrier to conceptual understanding? Implementing an interactive learning activity in South African undergraduate physics. *African Journal of Research in Mathematics, Science and Technology Education.*

V. Volkwyn, T. S., Airey, J., Gregorcic, B., & Linder, C. (2020). Developing representational competence: linking real-world motion to physics concepts through graphs. *Learning: Research and Practice*, *6*(1), 88–107. https://doi.org/10.1080/23735082.2020.1750670

All of the above publications were (or will be) published under full open-access licenses (CC-BY 4.0).

Supporting work

The following oral, poster and workshop presentations were delivered at academic conferences during the course of the PhD project, listed in chronological order:

i. Volkwyn, T. (2016). The Role of Mathematics in Learning Physics. Presented at the *First meeting of Graduate School in subject education research, Friiberghs Herrgård, Örsundsbro, Sept 5-6, 2016*. Abstract and presentation available for download from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-302646

ii. Volkwyn, T. (2016). Role of Mathematics in Learning Physics. Presented at the *Introduction to Subject Education PhD Course Conference, Blåsenhus Entrance Hall, Uppsala University, Uppsala, 8 November 2016*. Poster and abstract available from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-318513

iii. Volkwyn, T.S., Airey, J., Gregorcic, B., & Heijkenskjöld, F. (2016). Multimodal transduction in secondary school physics. Presented at the *8th International Conference on Multimodality, 7th-9th December 2016. Cape Town, South Africa*. Presentation and abstract available from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-316982

iv. Volkwyn, T.S., Airey, J., Gregorcic, B., Heijkenskjöld, F., & Linder, C. (2017). Teaching the movability of coordinate systems: Discovering disciplinary affordances. Presented at the *American Association of Physics Teachers 2017 Summer Meeting, 22-26 July, Cincinnati, OH, USA*. Abstract available from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-339408

v. Volkwyn, T.S., Airey, J., Gregorcic, B., Heijkenskjöld, F., & Linder, C. (2017). The IOLab and magnetic field – magnetic north versus actual direction. Presented at the *American Association of Physics Teachers 2017 Summer Meeting, 22-26 July, Cincinnati, OH, USA*. Abstract available from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-339410

vi. Volkwyn, T.S., Airey, J., Gregorcic, B., Heijkenskjöld, F., & Linder, C. (2017). Coordinating multiple resources to learn physics. Presented at the *American Association of Physics Teachers 2017 Summer Meeting, 22-26 July, Cincinnati, OH, USA*. Abstract available from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-339117

vii. Volkwyn, T.S., Airey, J., Gregorcic, B., Heijkenskjöld, F., & Linder, C. (2017). Physics students learning about abstract mathematical tools while engaging with “invisible" phenomena. Presented at the *Physics*

Education Research Conference 2017, July 26-27, Cincinnati, Ohio, USA, College Park, Maryland, USA: American Association of Physics Teachers. Abstract and poster available from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-344041

viii. Volkwyn, T.S., Airey, J., Gregorcic, B., Heijkenskjöld, F., & Linder, C. (2017). Working with magnetic field to learn about coordinate systems: a social semiotic approach. Presented at the *European Science Education Research Association 2017 Conference, 21-25 August, Dublin, Ireland*. Abstract and published extended abstract available from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-339549

ix. Volkwyn, T.S., Airey, J., Wikman, S., & Linder, C. (2017). Towards modelling formal learning in terms of the multimodal emergence of transduction. Presented at the *6th New Zealand Discourse Conference, Auckland, New Zealand, 06-09 December 2017*. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-340310

x. Volkwyn, T.S., Airey, J., Gregorcic, B., Heijkenskjöld, F., & Linder, C. (2018). Problem solving and coordinate systems: It's not all bout complicated calculations. Presented at the *Från forskning till fysikundervisning 2018, Lund, Sweden, 10-11 April.*, *Lund: Lund University Open Access*. Published abstract available from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-358673

xi. Volkwyn, T.S., Airey, J., Gregorcic, B., & Heijkenskjöld, F. (2018). Multimodal Transduction in Upper-secondary School Physics. Presented at the *International Science Education Conference (ISEC) 2018, 21 June 2018, National Institute of Education, Singapore*. Abstract and presentation available for download from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-354706

xii. Volkwyn, T., Airey, J., Gregorcic, B., & Heijkenskjöld, F. (2019). The Role of Transduction in the Teaching and Learning of Science: Students Learning about Magnetic Field. Presented at the *Lärarkonferens, Stockholm Univ., 7th May 2019*. Details available from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-417154

xiii. Volkwyn, T., Airey, J., Gregorcic, B., & Linder, C. (2019). A new explanation for why PER curriculum materials work. Presented at the *8th biennial Foundations and Frontiers in Physics Education Research Conference, Bar Harbor, Maine, 17-21 June 2019*. Poster available from http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-393539

Contents

Abbreviations

The following abbreviations are used in the text:

CADAA	computer-assisted data acquisition and analysis
CPS	cooperative problem solving
CPUT	Cape Peninsula University of Technology
DBER	discipline-based education research
IE	interactive engagement
FIPSE	Fund for the Improvement of Post-Secondary Education.
MBL	microcomputer-based labs
MDA	multimodal discourse analysis
MIT	Massachusetts Institute of Technology
PER	Physics Education Research
PERs	physics education researchers
SCALE-UP	Student-Centered Active Learning Environment with Upside-down Pedagogies *or* Student-Centered Activities for Large Enrollment Undergraduate Programs
SE	Science Education
SFL	systemic-functional linguistics
SF-MDA	systemic-functional multimodal discourse analysis
STEM	science, technology, engineering and mathematics
UCT	University of Cape Town
UU	Uppsala University
UUPER	Uppsala University Physics Education Research group
UWC	University of the Western Cape
UWPEG	University of Washington Physics Education Group

Preface

This Preface provides an account of how it came to pass that I uprooted myself from my home country, South Africa, to pursue PhD studies in Sweden, and how the central theme of this thesis came about. In telling this story, I, therefore, use personal pronouns and descriptions. Although I adopt the usual scientific style of writing, which employs the passive voice and third-person references, for the majority of the remainder of the thesis, in specific circumstances where I deem it appropriate to identify myself—as "I"—or my research team who worked with me on this project—as "we" or "our"—, personal pronouns will be used intentionally in specific circumstances.

This doctoral work represents for me far more than the 'redacted' contents of this thesis document. Infused into the thesis are my thoughts and perspectives about physics and the teaching and learning of the subject. These have emerged over many years, for I have worked with teams of experts in experimental physics research laboratories, have lectured to thousands of university students and engaged with them in teaching laboratories. Students have interacted with me in problem-solving sessions such as tutorials and consulted with me in one-on-one sessions. In the six years prior to commencing my doctoral studies, I had the privilege to learn from students as they engaged with each other, with their lecturers and teaching assistants in problem-solving tasks in interactive learning environments—these enriching experiences occurred while I was teaching on a physics course designed for students from educationally disadvantaged backgrounds at the University of the Western Cape (UWC) in Cape Town, South Africa.

My journey with this PhD study started with a strong commitment to build my knowledge of, and capacity in, providing access to university physics to students from disadvantaged backgrounds in South Africa. I have been teaching physics at the undergraduate level since 1991 and have been a full-time lecturer in physics at three South African universities since 2005. In early 2016 I started a research collaboration with the Physics Education Research group at Uppsala University (UUPER) in order to help improve the teaching and learning of physics at the undergraduate level, in particular the entry-level for educationally disadvantaged students. The division head and program professor of UUPER, Professor Cedric Linder, has maintained close ties with the University of the Western Cape (UWC) in Cape Town, South Africa, where he was the head of the Physics Department before taking up the professorship position in Sweden in 2000. Over the years, Professor Linder has fulfilled a key mentorship role for UWC Physics staff members such as myself and has remained committed to assisting the transformative work in the South African higher education context.

I applied for a full-time PhD position at Uppsala University in 2016 as, in addition to continuing the collaboration between UWC Physics and UUPER, I realised that exploring the theoretical aspects of physics (with respect to the teaching and learning thereof) being investigated by UUPER would further my aim to learn more about what it means to *do* and *learn* physics.

In a personal sense then, my thesis tells the story of how several of my questions and interests as a physicist and physics educator came together and were answered. Further, what seemed at first to be disparate elements—such as abstract mathematical tools, work with laboratory equipment, developing physics conceptual understanding, and developing representational competence—emerged as crucial links in the central thread of this thesis. More specifically, the research work brought together my interests in mathematics, representational competence, probeware and interactive engagement in physics work, in a way that produced an updated theoretical lens through which these aspects of physics work, which have been identified as important for learning physics, may be analysed. This will be introduced in the following sections of this chapter.

Mathematisation in physics teaching and learning

Students are known to struggle with mathematical conceptual understanding—see the discussion in Section 1.1.1. Clearly this situation can potentially have serious negative effects on physics teaching and learning. In the South African tertiary education context, where only 4% of learners leave school with a pass at the 50% level in mathematics (note that in South Africa the pass rate is actually only 30%), it is of paramount importance to ensure that students are afforded as much assistance as necessary to ensure success in their introductory mathematics and physics courses.

When the PhD position became available, I had already been working with the UUPER group as a visiting researcher for three months. Based on my experience of student difficulties in working with mathematical resources in physics learning situations, the broad initial objectives of the PhD were conceived as embarking on a series of studies to explore the teaching and learning relations between mathematical knowledge and constructing appropriate ways of understanding and applying these resources or tools for and in physics. As a physics educator at the introductory level, I had a number of unresolved teaching concerns. For instance, how could students, across a broad range of preparedness (from those deemed "well-prepared" to "under-prepared"), be helped to appropriately link their mathematical knowledge to proper understandings of physics concepts, and how could they learn about applying mathematical formalism in physics problem solving without losing sight of the underlying physics ideas? It has plagued my ‘physics teacher conscience’ that many of my students only displayed limited success in performing mathematical calculations, and those who were successful found it difficult to correctly interpret the results and extract the appropriate features of the physics information the problem was targeting. Moreover, it seemed to me that for students the mathematical equations took precedence over the physics on display in the other representational forms—for example, student-produced diagrams and other modelling representational formats often seemed to be completely disconnected from the choices students made when they proceeded to the mathematical solution to problems.

Representational competence in physics teaching and learning

More generally, difficulties with applying mathematics in physics are only part of the complex of learning challenges experienced by university entrants. In the South African context, based on both published[1] and anecdotal evidence, the issues of learning physics in a second language and the lack of meaningful exposure to working with laboratory equipment exacerbates matters. Further to this, my more than two decades of experience in teaching physics with a strategic multi-representational approach—verbal descriptions, sketches, diagrams, graphs, equations, etc.—, taught me that students find it hard to meaningfully connect all the different representational forms in a given task or problem, and to extract the intended conceptual understanding/s.

This ‘seat-of-the-pants’ awareness of a well-known learning difficulty within introductory physics courses seemed to be aligned with both the theoretical perspectives adopted by the UUPER team as well as a relatively underemphasised, yet important research area in PER, that of multi-representational problem solving and *representational competence*[2].

Initially my interests were simply to gain new insights into how to assist students to become more proficient in using a range of representational systems—e.g. diagrams, graphs and equations—to solve physics problems more effectively. My research journey however opened my eyes to the complexities of the learning challenges students encounter when applying these approaches in their work. For it is one thing to be able to solve a range of physics problems across different topics and in different situations in ways experts do. And it is another, arguably more complex teaching aim, for students to develop the

[1] Although this thesis does not attempt to address these issues directly, I provide the following reference as representative of the Southern African STEM (Science, Technology, Engineering, Mathematics) education research community’s interest in a broad range of socio-cultural factors affecting the learning of science subjects by African students of diverse backgrounds and languages. The sheer number of research articles on these issues is great,; a large number are published under the auspices of the *Southern African Association for Research in Mathematics, Science and Technology Education (SAARMSTE),* (for example, see Vale & Westaway, 2020).

[2] See Sections 3.3.1 and 6.4 of this thesis, as well as Paper V.

deeper understandings of the underlying physics concepts which physics educators claim as their primary learning goal for their students.

Probeware in physics teaching and learning

An 'Apartheid legacy'[3] effect on undergraduate science education in South Africa is the lack of experience that secondary school learners, particularly from disadvantaged communities, have in working with physics devices, especially in hands-on practical work. Anecdotal evidence suggests that one consequence of this lack of exposure is that many students enrolled in introductory level physics courses are unable to handle concepts and measurements from experimental work correctly.

A laboratory teaching tool, the *iOLab* (acronym for "an *i*nteractive *O*nline *Lab*oratory system"), developed by an expert team of physicists, engineers and physics education researchers at the University of Illinois Urbana-Champaign, had become available by the time I had started negotiating my collaboration with UUPER in 2015.

This *probeware*[4] tool was of interest to the UUPER group as it is a physics device designed specifically for pedagogical purposes, and one which possesses interesting features from a theoretical perspective. A research project investigating the teaching and learning advantages of such a laboratory teaching device therefore matched my interests with that of UUPER. Specifically, my interest in how such a tool could be used effectively in helping students from diverse backgrounds understand physics concepts better, and experience learning more directly—a 'promise' often linked to the deployment of such pedagogical aids.

Interactive engagement in physics teaching and learning

One feature of the South African schooling context is that learners are generally taught science in passive ways, where the teacher is the sole authority. During my time working with the PER group at UWC, as part of a team made up of two lecturers, an academic literacy expert, and trained teaching assistants, I focused on teaching on an *extended curriculum programme* (ECP)[5] physics course. These courses are an attempt by universities and the South

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[3] Apartheid was the system of legislated racial segregation that was enforced between 1948-1994. A cornerstone of Apartheid was an Education system which severely disadvantaged the majority of South Africans in terms of access to resources.

[4] Probeware is a term used to describe tools that allow users to interact with real-time updated information measured by sensors—see Tinker (2000).

[5] ECP courses have a long history in South Africa. Hutchings & Garraway (2010) provide a truncated compendium of ECP provisions in SA. They are essentially designed to give broader access to tertiary education to all population groups, who through previous educational disadvantage do not always meet the entrance requirements, especially in the more mathematical and technically oriented disciplines such as science, engineering, medicine, etc. For a broader perspective on the role of *Academic Development Programmes* in the history of South African Higher Education, see I. Scott (2009).

African educational authorities to boost the through-put rates of students from diverse backgrounds, learning in STEM (Science, Technology, Engineering, Mathematics) and other fields of study such as medicine. A typical design feature of such courses is that the first year of study is stretched over two years of full-time academic work.

At UWC, during the development of our ECP physics course, we adopted a less ambitious version of the SCALE-UP[6] classroom setup. This *active learning environment*, which has been shown by Beichner et al. (2007) to lead to better student learning outcomes, also promised to deliver on the UWC PER's aim to introduce students to the ways in which physicists, from a socio-cultural perspective, work collaboratively to co-construct physics meanings in discourse activities. The majority of classroom activities were therefore designed as *interactive engagement* (IE)[7] tasks, as opposed to the *traditional* approaches many physics lecturers at universities around the world still employ.

In addition, our Research Programme Professor, Cedric Linder had secured a major research grant from the Swedish Research Council (Vetenskapsrådet) which prompted the UUPER group to move towards investigating IE using a new methodology that, for the first time, combined social semiotics with variation theory in relation to students making meaning of physics (and chemistry) concepts.

A social-semiotic framework in physics teaching and learning

UUPER have been developing a social semiotic framework for the teaching and learning of physics since 2005—see for example Airey & Linder (2009, 2017). Key to this approach is viewing physics as a discourse, and asking what is required to effect meaningful learning of physics, and why this may be so.

When conceptualising my research with my supervisor, John Airey, I recognised the potential value of adopting an analytical approach that utilises a social semiotic framework to delve into the intricacies of analysing physics learning activities, especially interactive engagement tasks involving laboratory work with a probeware tool such as the iOLab. An initial project goal was therefore to explore ways to make the learning of new physics ideas more accessible to students within these types of learning environments.

I designed a pilot case study in 2016 to explore some of the issues discussed above. The preliminary analysis of the data showed a richness of resource-usage by students which involved them shifting meanings between semiotic systems in demonstrable ways in an interactive student-laboratory setting.

[6] SCALE-UP is an acronym for Student-Centered Activities for Large Enrollment Undergraduate Programs. More recently, the name behind the acronym has been amended—it now stands for Student-Centered Active Learning Environment with Upside-down Pedagogies.

[7] Interactive engagement (IE) is well-established in PER as a productive approach to achieving gains in student conceptual understandings—see the definition of Hake (1998) in Section 1.1.4, and note the contrast with traditional teaching approaches.

Therefore, in preparation for the 8th International Conference on Multimodality (8ICOM) which took place later that year, my supervisor suggested I might like to explore a social semiotic distinction between two types of movements of meanings – *transformation* and *transduction*[8]. Here, transduction seemed to be the most appropriate term to describe the students' usage of resources and I quickly realised that transductions were in fact inherently more powerful in learning situations than transformations. The central focus of my thesis then became investigating the role of transduction in physics in general and its importance for the teaching and learning of physics in particular.

Chapter 1, which follows, presents how these same interests informed the development of the research questions for the study.

[8] For this thesis, I use a definition from Bezemer & Kress (2008)—please refer to Sections 3.4.6 and 6.1 of this thesis for a full unpacking of this term within the updated social semiotic framework used and developed for this thesis.

1. Introduction

In the Preface I described my journey from being a university physics teacher to becoming a researcher in PER. My initial interests were in the role of mathematics in physics and the development of student representational competence. Through my initial pilot study, I also became interested in the use of probeware and the role of interactive engagement in the teaching and learning of university-level introductory physics courses. As mentioned in the preface, the distinction between transformation and transduction became central to my analysis of the initial pilot study where I quickly realised that transduction offered much greater possibilities for learning. It was transduction, then, that became the central pillar of this thesis.

In what follows I briefly introduce each of these aspects and show how they led to the research questions for this thesis. Thereafter I briefly describe my three case studies, and summarise my research articles. After a list of specialist terminology, I conclude this chapter with a synopsis of the thesis.

1.1. Research interests

1.1.1. Mathematics in Physics

This thesis work started with an awareness that Physics Education Research (PER) had begun to produce compelling evidence that many physics students either enter university or leave introductory courses lacking essential elements of *mathematics conceptual understanding* (for example, see Brahmia, 2019; Brahmia, Boudreaux, & Kanim, 2016; Shaffer & McDermott, 2005). That students struggle with mathematics concepts is well known[9]. For physics learning with mathematics (what has become known as 'mathematisation in physics' in PER), there is likely to be a range of negative outcomes, for example, severely limiting the possibility for students to work appropriately and productively with problem solving, and negatively affecting physics learning at the more advanced levels of study[10].

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[9] For example, I was struck by the work of Duval (2006) who analysed from a cognitive perspective the challenges for students learning mathematical concepts in an appropriate way.

[10] Note here the work of Brahmia, Olsho, Smith, & Boudreaux (2019); Christensen & Thompson (2012), and M. Eriksson, Linder, & Eriksson (2019), who showed that even in well-

My particular research interest here became how mathematics, as a representational system (semiotic resource system), links into the development of disciplinary-correct understandings of physics concepts in relation to what the mathematical resource system[11] affords for disciplinary-appropriate construction of physics concepts.

1.1.2. Multiple representations and representational competence

As discussed in Section 1.1.1 and in later chapters (Sections 2.3.3 and 3.3)[12], the problem of using mathematical resources in physics work is well-known and described in the literature. However, providing an adequate bridge for students between school and university physics is a multifaceted problem—students have to learn how to connect the semiotic material in a range of semiotic resource systems which give access to facets of physics concepts (see Airey & Linder, 2009). Mathematics is but one semiotic resource system used in physics.

Starting with the seminal research articles of Van Heuvelen (1991a, 1991b), some physics education researchers have pursued a research direction investigating the role of multiple representational systems in developing expert-like problem-solving abilities of students. These PER areas, of importance for this thesis, will be explored in more detail in the following chapters.

Further, for students to learn how to "think like a physicist" (Van Heuvelen, 1991a)—solving physics problems like experts—lecturers have to consider carefully how to assist them in bringing these multiple 'modes' of representation together in more meaningful ways. The notion of *representational competence* within the context of a multimodal social semiotic approach is adopted here. This is an important yet relatively unexplored area of research. This thesis seeks to add to our knowledge and understanding of how to develop students' representational competence when they are engaged in learning physics.

1.1.3. Probeware – pedagogical tools for physics learning

As discussed in the Preface, an early focus for this thesis work was the role of probeware, specifically the iOLab laboratory teaching tool. From a physics teaching perspective, this thesis explores, (i) giving students access to working

researched areas such as 1-D kinematics and algebraic signs, student difficulties with rudimentary mathematics concepts in physics persist.

[11] In this thesis each representational system is conceived of being constituted of a range of semiotic resources, which for physics have specific *meaning-making potentials* or *disciplinary affordances*. *Pedagogical affordances* refer to the usefulness of resources to learn physics, but are not necessarily used nor prized by the physics community as disciplinary (Airey, 2015).

[12] See also the discussion in Paper II.

meaningfully with physics devices, (ii) affording students hands-on experiences of real-world phenomena, and (iii) helping students learn how to connect their hands-on experiences to physics concepts.

From a theoretical perspective, this thesis seeks to deepen our understanding of how attributes of probeware tools (such as the iOLab) may be used in physics laboratory tasks to promote student conceptual understanding. In addition, there is an interest in how such tools could be used effectively so that students experience their learning as their own, i.e. construct meanings for themselves (a promise packaged with the deployment of the pedagogical advantages of probeware).

1.1.4. Interactive engagement

In a seminal paper, Hake (1998) established interactive engagement (IE) within PER to be a 'backbone' of effective tertiary level and high school physics curricula. Hake discusses interactive engagement as follows:

> …[activities] designed at least in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors, …
>
> (Hake, 1998, p. 65)

Central to his definition of IE methods is the requirement that students be actively engaged in activities that ensure peer-to-peer and peer-to-instructor feedback.

The conceptual framework described in Chapter 3 offers a lens that allowed me to explore the semiotic domain that exists between individuals when they make and remake meanings in physics communicative practices (such as students learning in IE laboratory tasks). I chose this framework with the anticipation that such an approach would lead to insights into what is required to effect meaningful learning of physics concepts in IE tasks, and why this may be so.

1.2. Developing social semiotic theory – transduction

Within the field of social semiotics, the term *transformation* is commonly used to describe the recasting of information *within the same semiotic system,* e.g. changing from one graph to another. A second term, *transduction*, is used to describe the recasting of information *within a different semiotic system* e.g. changing from a graph to an algebraic representation (see Bezemer & Kress, 2008, p. 169). As discussed in the Preface, my initial task in the research group was to establish whether the addition of this distinction to the existing theoretical framework developed in Uppsala could bring new insights to the field. This one decision affected the whole course of this thesis.

In a pilot case study, a laboratory task was developed for use in university settings, where the primary purpose of the study was to establish whether adding a distinction between transformation and transduction would contribute to the development of the multimodal social semiotic framework for the teaching and learning of physics.

It was also anticipated that findings of the study would contribute to our understanding of how students may learn physics more productively. Whilst at the same time, providing physics lecturers with nuanced insights into how to assist students to this end.

The richness of the empirical data generated from the pilot study set the research on a path that firmly established transduction as the central theme of this thesis. Transduction was thus incorporated in a fundamental way into the conceptual framework—details in Chapter 3—and became the basis for analysing the empirical data generated in all three case studies used (see Section 1.4). To this end my overarching research question for the thesis was framed in terms of transduction.

1.3. Research questions

Overarching research question:

> *What might transduction—a theoretical construct common in the field of multimodal social semiotics—contribute to social semiotics research work in PER?*

In attempting to answer the overarching research question, the following six research questions emerged:

- *RQ1. How can the role and functions of physics devices be described when applying the social semiotic lens used in this thesis?*
- *RQ2. Based on the answers to RQ1, how can the concept of transduction be used in this thesis to extend our understanding of the role and function of probeware in physics teaching and learning activities?*
- *RQ3. In what ways might a transduction perspective supplement our understanding of why interactive engagement is an effective strategy in physics education?*

RQ4. How can the application of social semiotics help us design tasks where students gain initial access to mathematical concepts for physics without the necessity for calculation?

RQ5. Using the lens of social semiotics, what is the role of student representational competence in learning 1-D kinematics and how can such competence be developed?

RQ6. How can the results from RQ5 be used to propose a generalised way of developing representational competence in physics education?

The answering of these research questions provided a multiple feedback loop in which a social semiotic framework in PER—as championed by UUPER, and within which my conceptual framework is grounded—was updated, the methodological and analytical tools implemented for the thesis were developed and refined, and the IE laboratory tasks utilising the iOLab were also rewritten and updated. In addition, while designing and doing the research, a number of contributions to the field of PER emerged. These are included in the summary given in Chapter 7.

1.4. The case studies

The research design of the thesis work followed a *flexible qualitative*[13] approach to case study research—this is discussed in more detail in Chapter 4 (Methodology). The thesis used three such case studies:

A. Learning about magnetic field and coordinate systems (Sweden)

Case Study (A) (elsewhere in this thesis also referred to as the pilot study) was undertaken in Sweden. Since the principal researcher came from a background of introductory university physics in South Africa, students doing advanced level physics at a Swedish *gymnasiet*[14] were chosen as a suitably comparable student cohort.

This case study was designed around using a probeware tool (the iOLab) to study the Earth's magnetic field. The iOLab's magnetometer was used to display graphs of the three Cartesian components of the magnetic field in real-time. Students worked in pairs with an open-ended interactive engagement

[13] See Robson & McCartan (2016) for a discussion about *flexible* research designs within the *qualitative* paradigm of what they refer to as "real world" research. More will be said about this in Chapter 4 of this thesis.

[14] For readers unfamiliar with the Swedish schooling system, gymnasiet schools, or gymnasiums in English, are upper secondary schools (final three years of secondary education), whose programmes offer students the qualifications needed to further their studies at higher education institutions.

task to determine the direction of the magnetic field. It was envisaged that the students would need to use a range of semiotic resources in solving the task. In this way the task design addressed the four major research interests explored in this thesis.

The details of Case Study (A) are given in Section 5.1.1.

B. Learning about magnetic field and coordinate systems (South Africa)

In Case Study (B), the identical task designed for Case Study (A) was carried out with groups of South African university students in their extended, first-year course in physics. Interestingly, the South of Sweden and South Africa are positioned north and south, respectively, relative to the Earth's geomagnetic equator so that the magnetic field points into the Earth in the South of Sweden and out of the Earth in most of South Africa at a similar angle.

The details of this Case Study (B) are given in Section 5.1.2.

C. Learning about graphs of motion in 1D-kinematics (Sweden)

Case Study (C) used the wheel sensor on the iOLab to graphically display movement. As explained in Section 1.1.2, a central interest of this thesis is how students appropriately connect particular semiotic systems (in this case graphs) to physics concepts (in this case 1D-kinematics).

Here, the student cohort comprised of students enrolled in a physics teacher-trainee programme at a research university in Sweden. The students worked in pairs with the iOLab in order to create certain "shapes" in position-time, velocity-time and acceleration-time graphs.

The details of Case Study (C) are given in Section 5.1.3.

1.5. Summary of the research articles

This thesis is primarily written around five research papers. A short description of each paper is given below:

Paper I

This Physics Education Research Conference (*PERC2017*) proceedings paper was the first published article from the thesis work. Although the theoretical terminology used in subsequent articles was not employed here, this paper introduced much of the research interests of the thesis. Space constraints—length of papers is restricted to four double-columned pages—precluded the unpacking of the full meaning of the term transduction, despite my presenting these ideas at the earlier 8ICOM conference mentioned in the Preface. Case Study (A) provided the data and context for the reported findings and discussion. Importantly, the paper hints at the importance of attending to the dynamic meaning-making moves that students and facilitators make when working with multiple semiotic resource systems in interactive engagement tasks.

Paper II

This paper was published in the *European Journal of Physics*. In this paper, the problem around students' difficulties in coming to apprehend a key affordance of coordinate systems, its movability, is unpacked for a readership comprising physicists and chiefly university-level physics educators. Important empirical findings were reported in this paper that shed light on the difficulties students experience in working with abstract mathematical tools whilst learning about invisible phenomena in laboratory settings. Case Study (A) formed the basis of the work reported in Paper II.

Paper III

This research paper, published in *Designs for Learning*, presents the pivotal theoretical findings of this thesis work. In this article, the central role of transduction in physics and the teaching and learning of physics is discussed in detail. Case Study (A) formed the basis for the reported findings.

Paper IV

This paper used data from Case Study (B) and at the time of printing of this thesis, was being prepared for submission to the *African Journal of Research in Mathematics, Science, and Technology Education*. An important finding is the reticence of South African students to use alternative semiotic resources when a mathematical route to problem solution is possible.

Paper V

This paper was published in *Learning: Research and* Practice and is based on Case Study (C). The paper reports on theoretical and empirical work in the area of representational competence. As such, this paper represents the culmination of my entire PhD research project. All the theoretical and empirical work that makes up my PhD are showcased and applied in an actual, authentic learning laboratory at the university level.

1.6. Thesis synopsis

Chapter 1 has served as the introduction to the work presented in this thesis. I have introduced the reader to my research interest which led to the development of my research questions. The next chapter (2) serves as a broad introduction to the field of PER. In so doing I have attempted to lead the reader to the aspects of PER that I see as the foundations for the theoretical framing given in Chapter 3. Hence, Chapter 3 should be seen as an integral part of situating my work. Chapter 3 describes the conceptual framework applied and developed for this thesis, and provides a basis for the methodology described in Chapter 4. Chapter 5 provides the details of the data collection and analysis undertaken in the case studies. Chapter 6 provides a discussion that draws together the theoretical and empirical findings in a synergistic way, and answers the research questions. Chapter 7 provides a summary of my theoretical and empirical findings and also includes suggested implications for the teaching and learning of physics. Chapter 8 presents my thoughts on possible future research work, and the last chapter (9) provides a summary of the thesis in Swedish.

1.7. Glossary of terms used in the thesis

The following list serves to summarise key words, phrases and terms used in the text, in alphabetical order. The descriptions specify the way the terms are used in the thesis. Italicised text denotes terms explained elsewhere in the list. If abbreviations of terms and phrases are used in the text, they are provided in brackets.

active learning:

a term used by several researchers to describe non-traditional physics teaching and learning approaches; a well-known example is the "Active Learning Guide" developed by the PER team at Rutgers university. This student learning aid focuses on approaching problems from an experiential and experimental point of view.

cooperative problem solving (CPS):

a recitation approach developed by Pat and Ken Heller and their collaborators at the University of Minnesota, centred around a group-learning problem-solving environment.

coordinating hub:

a term appropriated by *UUPER* for their framework of looking into students' engagements with multiple representations or semiotic systems. It is a persistent representation around which meanings may be made with other resources available in any given task.

disciplinary discourse:

the complex of systems of semiotic resources which make up a discipline; the use of these in parts or greater constellations communicate disciplinary meaning/s (Airey & Linder, 2009).

disciplinary affordance (DA):

the agreed meaning-making functions that a semiotic resource fulfils for a particular disciplinary community; in other words, it is the inherent potential of a resource to provide access to disciplinary knowledge (Airey, 2014; Fredlund, Airey, & Linder, 2012).

interactive engagement (IE):
Hake (1998, p. 65) provides the following definition: "… [activities] designed at least in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors, …".

metafunction:
a term originating in SFL, thought to be possessed by all languages, and relate to the semantic structure of language—all languages are believed to be shaped and organised in relation to the three metafunctions; ideational, interpersonal, and textual.

mode:
when used within the multimodality framework, the use of the word is analogous to the communication aspects of signs derived from SFL, i.e. a mode necessarily has to possess the three *metafunctions*. However, for this thesis, the word is simply used as a label for a specific meaning-making function of some semiotic resource system within a given context or social setting.

multimodal social semiotics (MMS):
this approach has the premise that learning can be investigated from a meaning-making perspective in all the socially organised resources (*modes*) peculiar to a particular social group (see *multimodality* and *social semiotics*).

multimodality:
a relatively young, but well established research tradition introduced by researchers—notable scholars here are Gunther Kress and Theo Van Leeuwen—working in the field of social semiotics, that provides a framework or 'language' to describe the meaning-making functions of resources other than language (e.g. diagrams, representations, images, etc.)—(Bezemer, Diamantopoulou, Jewitt, Kress, & Mavers, 2012; Jewitt, Bezemer, & O'Halloran, 2016; Kress & Van Leeuwen, 2006).

pedagogical affordance (PA):
the appropriateness of a semiotic resource for teaching some educational content (Airey, 2015).

real-world phenomena:

this term refers specifically to natural phenomena that are experienced by humans by way of direct sensory interaction with environmental input (sight, sound, touch, etc.) or via another mode that allows perception through the senses (for example, a compass needle pointing to magnetic north).

resources:

unless stated otherwise, this word refers to the meaning-making affordances of a range of tools, representations, and procedures, which may be used in physics disciplinary practices.

semiotic resource:

a tool, activity or representation which, when used or engaged with, allows for the articulation and expression of meaning in a discursive or communicative practice of a particular group of people (a family or social group).

semiotic resource system:

this terminology is used in the thesis to refer to any system of disciplinary representations, tools or procedures which encompass a range of distinct but connected meaning-bearing resources.

semiotics:

the study of processes which produce signs and symbols for making meanings, and their interpretation—see *multimodality* and *social semiotics.*

social semiotics:

a branch of research that is closely related to and shares its origins with systemic functional linguistics (SFL) for which a main ontological commitment is the notion that the meaning-making functions of discourses are established in the shared communicative practices of social groups or disciplinary communities. Within these practices shared understandings are constantly shifting and being updated with the established sociocultural meanings as a platform for new meanings generated within the communicative practices of groups and disciplines (Van Leeuwen, 2005). Researchers in this field have attempted to broaden the study of communication modes beyond the purely linguistic channels.

systemic functional linguistics (SFL):

an approach to language that is based on two main theoretical stances—language as an act of communication involves choices represented by a sort of 'system network' (see Halliday, 1961, who took the notion of system from his teacher, J. R. Firth), and that language evolved under pressure of the functions that language must serve, which through three metafunctions (interpersonal, textual, ideational) have effect on the structure and organisation of language. In SFL, language is therefore considered as a social semiotic system.

transduction

taken from the field of multimodal social semiotics, it is the movement of meanings (or 'semiotic material') from one semiotic resource system to another, for example, from words to pictures (see Bezemer & Kress, 2008; Kress, 2010).

transformation

taken from the field of multimodal social semiotics, it is the movement of meanings (or 'semiotic material') within a semiotic resource system, for example from one diagram to another (see Bezemer & Kress, 2008; Kress, 2010).

UUPER framework:

the social semiotics-based theoretical framework having been developed by the Physics Education Group at Uppsala University; in this thesis this term is mostly used to describe the pre-existing framework before I joined the group in 2016. See Chapter 3 and in particular Section 3.4 for a full description.

2. PER – a literature review

2.1. Introduction

This thesis work is situated in the Physics Education Research programme in the Department of Physics and Astronomy at Uppsala University and although it could be seen as an example of discipline-based education research[15] (DBER) I have chosen to directly situate it in the disciplinary domain of physics education research (PER). In doing so, I present an overview of PER to show how I see my research fitting into a broader PER aim of contributing to a finer understanding of how disciplinary science content may be unpacked and analysed to advance the teaching and learning of physics. I do this by presenting a nuanced historical description of the field of PER and end off by laying the foundations for building my conceptual framing in Chapter 3.

This chapter then serves as a broad introduction to the field of PER; the situating of my work will be given mainly in Chapters 3 and 6.

2.2. Physics education research (PER) in the USA

PER has its roots in the United States. The organisation and promotion of science and engineering disciplines in the USA can be traced back to the establishment of the American Association for the Advancement of Science in 1848 (AAAS, 2020) and the American Association of Physics Teachers in 1930 (AAPT, 2020a). The founding members of the AAPT were committed to, *"the dissemination of knowledge of physics, particularly by way of teaching*." In contrast, the current mission statement of the organisation states that the AAPT is "*a professional membership association of scientists dedicated to enhancing the understanding and appreciation of physics through teaching*." The creation of the Physical Sciences Study Committee (PSSC) at the Massachusetts Institute of Technology (MIT) in 1956, by a group of university and school educators (AAPT, 2020b), led to the first modern identification of factors that hinder effective learning in the physical sciences—problems of student interest, not thinking like physicists, and not being able to solve physics problems like physicists do.

[15] See the U.S. National Research Council report edited by Singer, Nielsen, & Schweingruber (2012), and more recently, Talanquer (2014), who provide descriptions and an unpacking of DBER's goals.

Then there was Sputnik…

On 4th October 1957, the Soviet Union fired the starting shot for the space race with the United States by successfully launching and placing into low Earth orbit the first artificial satellite, Sputnik 1 (NASA, 2017). The damaging effects this had on the American psyche are well documented (A. J. Scott, 2007)—as a further example, consider the presidential speech a month later by Dwight D. Eisenhower (US National Archives, 2010). In response, the US government almost immediately replaced the National Advisory Committee for Aeronautics (NACA) which had served the USA for over four decades, with the National Aeronautics and Space Administration (NASA – founded 29th July 1958), and rapidly ramped up its funding from 0.1% of the US Federal Budget in 1958 to a peak of 4.41% in 1966 (Steinberg, 2011).

One spinoff of this resolute effort to win the space race was a focus on training more and better qualified scientists and engineers. To address a fear among the American STEM community that Soviet children were outlearning their own in the vital subjects of physics and mathematics, the USA government brought into law on 2nd September 1958 the National Defense Education Act (NDEA, 1958). With this act, so called 'softer' approaches to educating young adults which had become popular after the Second World War—for example, the *life adjustment movement* headed by the well-known 20th century vocational educator Charles Prosser (Silver, 1991)—were relegated in favour of 'harder' ones which had clear discipline-linked skills and outcomes (NSF, 2020a). The NDEA thus marked the start of (i) a greater governmental role in American education, and (ii) a greater focus on and commitment to education in physics and mathematics.

The additional federal funding provided for science learning projects in the post-Sputnik period attracted university academics who would perhaps not normally have been interested in pursuing educational concerns. This was due to the access to resources and the prestige associated with receiving federal grants (Cummings, 2011). In addition, as Cummings comments:

> Sputnik left government officials and educators alike with a new (perhaps nebulous) sense that the nation could no longer allow learning physics to be left to only the few who "have what it takes" to make it successfully through our physics courses.
>
> (Cummings, 2011, p. 4)

An additional early driver for the creation of the field of physics education research was the Science Curriculum Improvement Study (SCIS), a fifteen-year project that started in 1961 (Cummings, 2011; Kratochvil & Crawford, 1971). In addition, the National Science Foundation (NSF) of the USA, in contributing to the space race effort, started funding research into science learning in the early 1960s, adopting SCIS as a key project (NSF, 2020b).

This combination of factors—reclaiming American national prestige by winning the space race, political commitment at the highest levels, a national drive to create more physicists, and funding for science research and learning projects—created the fertile soil in which the fledgling field of PER germinated.

Most scholars agree that PER as an organised discipline started in the 1970s (Cummings, 2011). For a recent review of the PER field in the US, see Docktor & Mestre, (2014). However, it is clear that research in physics education had already started in the 1950s (see the previous paragraphs). Although the journal *Physics Education* was established in 1966 with the express aim of catering for research about teaching physics at the secondary school and introductory university levels, it took some time to receive significant attention from university educators. One possible reason may have been that there was not as yet much hard evidence for specific problems with student learning of basic physics concepts or skills. Edward ("Joe") Redish, who was to become one of the most influential contributors to PER in the mid-1990's and beyond, recounts an episode in his much-used resource for university physics educators, *Teaching Physics with the Physics Suite* (Redish, 2003b). He describes how his perception of his teaching (in relation to what his students were learning) changed by being confronted with empirical evidence. In a sub-section titled, "*I wouldn't have believed it if I hadn't seen it*", he admits to only starting to take seriously a basic student conceptual problem after being confronted with solid research data (Redish, 2003b, p. 14). This empirical and evidential basis for PER was to become a foundation on which much of the field was built. The springboard for much of the early research in PER was individual instructors noticing their students' difficulties in learning physics concepts, deemed to be rudimentary from their perspective.

A cursory overview of work published in the 1970's—based chiefly on Docktor & Mestre (2014)—highlights the early interests in students' conceptual development and problem-solving abilities. Topics in mechanics—a foundational and stable knowledge base in physics for four centuries—became the substrate for exploring students' development of concepts, thinking, and/or reasoning skills (Karplus, 1977; Keil, 1979; Reif & St. John, 1979). Other early work homed in on problem-solving abilities with the aid of representations and/or the crude computer aided technologies of the time (Larkin, 1979; Newell & Simon, 1972; Sherwood, 1971; S. G. Smith & Sherwood, 1976). Although at this stage there was no widespread effort put into research into laboratory work, notable exceptions are the works of Reif & St. John (1979), albeit with a focus on "physicists' thinking skills", and Reid & Arseneau (1971), who, even in those early years of research in this field, reported on a laboratory programme which coordinated the use of audio-visual aids, open-ended laboratory experiences and computational modes and aids.

As more and more university educators started realising that their students were not grasping ideas as they had always assumed, the 1980's saw an increased interest in establishing which keystone concepts physics students need to learn. This led to a plethora of studies into student *misconceptions*—elsewhere in the literature referred to as *alternative* or *naïve* conceptions, or intuitive or naïve beliefs or theories—in a wide range of topics (see Docktor & Mestre, 2014).

Research into student misconceptions in the 1970's and 1980's led to the development of widely available concept inventories by the early 1990's. The most well-known example of a concept inventory is that developed by David Hestenes and his PhD students—the Force Concept Inventory, or FCI (Hestenes, Wells, & Swackhamer, 1992).

The impact on teaching awareness of this branch of PER work is recounted by Eric Mazur, a seasoned and well-liked physics educator in that decade and beyond, who came to the realisation that his 'bright' students were not grasping the 'basic' and hence foundational concepts in his courses. After inspecting a concept inventory survey instrument from a PER paper in 1985 (Halloun & Hestenes, 1985), Mazur decided to confirm the 'superiority' of his Harvard students by giving them the survey instrument, which by his estimation contained many 'trivial' questions. The outcome shocked him—his students fared little better than the student groups reported in the literature. This finding led Mazur to begin research into his own teaching—for example, he found that proficiency in solving problems is not necessarily coupled with understanding the underlying physics concepts (Mazur, 1992). A half decade later he published the popular physics education resource, *Peer Instruction*, in which he incorporated much of what he had learnt from PER at the time, and his own research and experiences (Mazur, 1997).

By far the majority of the inventories deal with specific physics topics. However, the *Lawson Classroom Test of Scientific Reasoning* (LCTSR) (Lawson, 1978) does attempt to address some of the more general aspects of scientific reasoning (e.g. ideas around conservation, proportional thinking, and hypothetic-deductive reasoning). This demonstrates an awareness by some scholars of the importance of these elements in producing students with a more holistic view of physics knowledge.

The perspectives gained from these types of findings from PER in the formative years resulted in a concerted effort during the 1990's to not only help improve students' conceptual understanding, but also to design strategies, curricula and interventions to teach physics in more explicit ways. This is evidenced in Arnold Arons (1990), *A Guide to Introductory Physics Teaching*, where he addresses teaching specific physics topics through a lens of students conceptual and reasoning difficulties, and other problems of learning and understanding physics based on earlier PER research. McDermott and her colleagues and students at the University of Washington Physics Education

Group (UWPEG) produced the teaching resources, *Tutorials in Introductory Physics* (McDermott, Shaffer, & University of Washington Physics Education Group, 2002), and *Physics by Inquiry* (McDermott & University of Washington Physics Education Group, 1996a, 1996b) with an underlying theme of fore-grounding inquiry, not mere calculation, as the vehicle of learning to become a physicist. These interventions targeted specific student difficulties and were designed around using operational definitions. The *Activity-Based Physics Project* (University of Washington Physics Education Group, 2002) generated models for physics teaching and learning, such as, *Workshop Physics* (WP; see Laws, 1997), *Interactive Lecture Demonstrations* (ILD; see Sokoloff & Thornton, 2006), and *Real Time Physics* (RTP; see Sokoloff, Thornton, & Laws, 2011). These are based on UWPEG's models, integrating other technologies like *computer-assisted data acquisition and analysis* (CA-DAA). Later, in the early 2000's Edward Redish produced the resource *Teaching Physics with the Physics Suite* (Redish, 2003b).

2.3. Mapping the field of PER

In this section the evolution of the main avenues of research present in PER in the US today will be set out. The first subsection provides an overview of the field and the *raison d'être* of current PER, based principally on the main themes identified in the PER review paper by Docktor and Mestre (2014). Other review articles do exist (Beichner, 2009; Cummings, 2011), and will be drawn on in parts of the sections which follow.

2.3.1. The current state of PER

Initially, physics education researchers restricted themselves to employing research methods they were familiar with from their evidence, experimentation and statistical rigour (McDermott & Redish, 1999). This is understandable, considering the challenges faced by many researchers in the field—problems of acceptance as 'proper' physicists (Barthelemy, Henderson, & Grunert, 2013) and legitimate researchers (Beichner, 2009; Cummings, 2011; McDermott, 2001), and the role of PER staff being seen as that of providing teaching support rather than producers of *bona fide* physics research (Heron & Meltzer, 2005). Today, the field has grown such that over 90 universities in the USA now have Physics Departments with established PER groups, with a further 16 international groups registered with *PER Central*, an online resource collection published by the AAPT (AAPT, 2020b). In 1999, the American Physical Society (APS) released a statement, confirming that PER should be considered as a natural and integral part of physics departments and that the research produced should be classed as mainstream physics research (APS, 1999). Consequently, PER can be considered today to be a well-established branch of physics academic work.

When physics educators combined their findings about conceptual understanding and problem solving, "interactive engagement"[16] (IE) strategies emerged as a key method to address many of the identified learning challenges (Beichner et al., 2007; Hake, 1998; Mazur, 1997). The reader is again referred back to Section 1.1.4 or the Glossary (Section 1.7) for how this thesis uses the term interactive engagement.

More recently, there has been an ever wider adoption of computer-aided methods and use of 'microcomputer-based laboratory tools' (MBL)—see Thornton (1987) for an earlier application. More recently, the term "probeware" is replacing "MBL" to more accurately reflect the great strides in technology, computer chip power, and the wide range of devices which can now perform the functions of the microcomputer of the 1980s and 1990s, and more—see the report article by Robert Tinker (2000) and the journal article by Metcalf & Tinker (2004). These new technologies are of course based on CADAA (see earlier discussion in Section 2.2). These kinds of tools have been purposefully developed based on the principles of '*active learning*', i.e. actively engaging students. Tinker (2000) claims that hands-on work with aptly designed laboratory apparatus leads to students developing more intuitive understandings of complex phenomena. Some scholars have also used the term '*inquiry-based learning'* to characterise laboratory teaching approaches that forefront students' self-discovery of scientific principles. The work by Sokoloff and his team based at the University of Oregon, has made a major contribution to the field, e.g. *Interactive Lecture Demonstrations* (ILDs, Sokoloff & Thornton, 2006) and the *Real Time Physics* (RTP) *Active Learning Laboratories* (Sokoloff et al., 2011). More recently, the iOLab Wireless Lab system has been developed—iOLab is an acronym for *interactive online laboratory system* (Selen, 2013). The system includes a hand-held device which communicates wirelessly with a computer, allowing for a high degree of autonomy for students (the device can be moved around at will). With multiple on-board sensors, the system allows exploration of a wide range of physical phenomena. The iOLab, with its multiple ways of making disciplinary meanings accessible for students, is a central aspect of this thesis—see Section 5.2.

2.3.2. From conceptual understanding to curriculum reform

Based on the beginnings of PER, it is understandable that the focus has been on developing improved instructional tools and environments so that students can learn physics more effectively and be better prepared for more advanced

[16] IE has its origins in the work of John Dewey (1938), who championed experiential learning, and pointed to the importance of the social and interactive dimensions of the learning process.

studies. Informed by cognitive science and cognitive psychology, much of the earlier research can be described as problematizing student difficulties as falling into either a conceptual understanding or problem-solving framework.

Perspectives from cognitive science

PER scholars started to think about the fruitfulness of applying breakthroughs in cognitive science to physics learning. For example, Redish (1994) deduced some principles which he collected and organised into a 'mental architecture' of 'mental models' to characterise the complexity of what students may be thinking (and not what they know or don't know)[17]. In contrast to the more unfamiliar social science disciplines, cognitive psychologists employed tools and techniques familiar to physicists. Underpinned by empiricism, PER researchers proceeded to catalogue student misconceptions and how experts solve problems—see the next section—as compared with students (described as novices). Out of these efforts, a vast array of research instruments—to test conceptual understanding—and instructional strategies (or surveys) and interventions have been developed. The ultimate goal was to aid physics educators in overcoming student difficulties with these two keystones of what it takes to be a competent physicist—recall that the space race required not only more physicists, but ones who were highly competent and creative, with proficiency in problem solving identified as a critical skill. For a review of the array of concept tests developed to test the effectiveness of physics curricula in moving students to better understandings across a broad range of physics topics, see Docktor & Mestre (2014, p. 24).

When looking at the branch of PER concerned with conceptual understanding, there seems to be a sort of 'pre-ontological' pondering about *how students think*. It is important to note here that physicists and therefore physics education researchers start with their own ontological framing that holds there is a reality 'out there'. In addition, many PER researchers are of the view that students' use of concepts is a manifestation of the function of 'inner-brain' activity. This means that if you could characterise and adequately map the brain architecture, this might shed light on how to change ideas or form new, more correct conceptions. As a consequence, the '*conceptual change*' paradigm of trying to understand how students come to understand (or not understand) scientific concepts has had a major influence on the trajectory of theory development in PER. Conceptual change was first put forward by Posner, Strike, Hewson, & Gertzog (1982). However, (Linder, 1993) challenged the notion

[17] Joe Redish (2003b) collected many of the findings in the area of knowledge, memory, and activation in his teaching resource, *Teaching physics with the physics suite*. In addition, he compiled all his explorations into cognitive science and cognitive psychology for PER into what he terms a *Theoretical framework for physics education research: modelling student thinking*—this is the title of a paper presented at the International School of Physics in Varenna, Italy (Redish, 2003a). Herein, Redish lays out the structure and workings of *long term memory*, *working memory* and *short term memory*.

of conceptual change, and proposed instead a focus on "enhancing students' capabilities to distinguish between conceptualizations in a manner appropriate to some specific context—in other words, being able to appreciate the functional appropriateness of one, or more, of their conceptions in a particular context,…" (Linder, 1993, p. 298). This orientation allows for attention to be given to students' own conceptualisations when they perform physics tasks.

Over the years, different perspectives relating to conceptual change or the construction of concepts were developed. The '*knowledge-in-pieces*' view first put forward and championed by diSessa (1988) is a form of constructivism that holds that both naïve and scientific conceptual understanding are grounded in phenomenological primitives (or '*p-prims*'). This means that an individual's conception about something is neither correct nor incorrect; rather, p-prims are in fact resources for new learning. Correct scientific conceptions can then be constructed upon the multiple smaller resources which make up the holistic conceptions which science educators are aiming for. The knowledge-in-pieces perspective has catalysed other notable theoretical views or frameworks, notably the '*resources*'[18] framework view held by Hammer and others (e.g. Hammer, 1996; Hammer, Elby, Scherr, & Redish, 2005), the '*facets*' view of Minstrell (1992), and the '*ontological categories*' perspective attributed to Chi and her colleagues (e.g. Chi, Slotta, & De Leeuw, 1994). Much of this early theoretical work is grounded in ideas from cognitive psychology and neuroscience.

Constructionism versus constructivism

Until recently, there has not been much concerted effort in exploring or developing *learning theories* in PER (also see the discussion in Section 2.4). This is despite the leveraging and appropriation of frameworks drawn from the cognitive sciences and education research. Basically, a learning theory is simply a conceptual framework describing how information is 'accessed', 'absorbed', 'processed' and 'retained' during learning (Knud, 2004; Ormrod & Jones, 2018). Cognition (thinking), attitudes and beliefs (driven by emotions), prior experience (sociocultural factors and pre-existing knowledge), as well as the learner's environment (activities, etc.) all impact on how any individual may come to a new or updated understanding (or 'world view') about how things work and what they could mean. Success in learning may be observable by the appropriate application of new knowledge in new situations and across contexts, and the retention of acquired skills.

[18] So far, the word 'resources' has been used in this thesis to describe the scientific tools, procedures, representations, etc., for working in a scientific field. Here, Hammer and Redish are referring to in-brain or cognitive resources, i.e. they refer to mental processes which are activated when thinking work is required to do scientific tasks.

For most PER researchers, modern thinking around how best to sequence learning tasks and curricula is generally ascribed to *constructivism*—as attested to by the following quote from Docktor & Mestre (2014, p. 14), "Most modern theories of instructional design for science courses are based on constructivism and its associated theories, such as situated, sociocultural, ecological, everyday, and distributed cognition" (Jonassen, 2000).

Constructivism has its roots in Piagetian frameworks. In Piagetian theories—see Gerson & Primrose (1977) for an early application to engineering and science learning—mental structures or schema develop over time, and learners cannot perceive new 'things' until they have a mental structure with which to perceive them. Piaget's *genetic epistemology* involves several stages of development of mental structures in children from sensori-motor (0-2 years) followed in order by pre-, concrete, and formal operational stages (2-17 years). Early PER scholars have picked up on this model as it seemed to encapsulate well the identified problem of helping students of physics (or science in general) traverse the "concrete-formal gap"[19]—see for example Renner & Lawson (1973). The literature is replete with evidence that the acquisition of scientific knowledge is not static; however, there is still no complete nor agreed understanding on *how* this learning (change in mental structure) occurs, especially in official science learning contexts.

Seymour Papert—the 'father' of *constructionism*—on the other hand, was more interested in *how* people learn *with*, and especially in relation to, the artefacts in their surroundings and in the creation of learning 'productions'. Papert's conceptualisation of knowledge is both *situated* and *pragmatic*—inextricably context dependent and bound to external supports (e.g. tools) (Ackermann, 2001). Piagetian constructivists focus on the increasing abstraction of mental models within the developmental stages of adapting the brain's internal structure and organisation of knowledge. Papertian constructionists on the other hand rather pay attention to the *in-situ* aspects of learning—gaining a 'feel' for the environment, 'experiencing' by immersion 'in' the phenomenon being studied—and therefore are more interested in the tenuous transitions which occur when new learning occurs as a dynamic process of change.

Airey & Linder (2009) proposed a framework of physics teaching and learning—see Chapter 3—, which aligns with how their students may come to apprehend new knowledge for themselves. Now comes into focus what to select, from an array of tools and representations, for effective learning in a specific disciplinary task. Even though physicists on the whole believe an objective real world exists, personal knowledge of it has to be constructed by the individual in specific disciplinary contexts, as part of a scientific community—knowledge is by necessity simultaneously an individual *and* a social construction. As such the *social constructivist* paradigm abounds in PER, even

[19] The c*oncrete operational* thinker needs experience with objects and the *formal operational* thinker can activate abstract thought in reasoning without the direct need for objects.

though many researchers do not explicitly tie themselves to any particular educational learning theory.

The p-prims of diSessa can now be seen as part of a cognitive architecture that underscores the constructivist thinking around learning in physics. From a simplistic view of holding misconceptions, knowledge accrual can now be viewed as a dynamic process in which the activation of pieces or (mental) *resources* in memory becomes refined with repetition and adaptation (diSessa, 1988). In this way it is possible to construct or 'compile' stable scientific concepts by repeated exposure to and rehearsal of tasks across similar situations and contexts.

Cognitive psychology

Cognitive psychology has also made a significant impact on the work of physics education researchers. Well-known scholars such as Hammer and Redish together with other colleagues have developed the *resources framework* (Hammer, 1996; Hammer et al., 2005), leveraging many principles and concepts borrowed from cognitive science and cognitive psychology that attempts to figure out how the functioning of the brain may affect and effect the development of new understandings. In contrast to the resources framework of Hammer and Redish, the overarching conceptual framework developed in and for this thesis, is constructed from a social semiotic perspective on the teaching and learning of physics developed at Uppsala University in Sweden over the last fifteen years—see Airey & Linder (2017) for an updated view of this framework, which will be unpacked fully in Chapter 3. This perspective is suitable for attending to students in-situ learning within the disciplinary spaces of learning; it provides an analytic approach to study the in-the-moment semiotic activity which is characteristic of the dynamic interaction made possible with aptly designed IE physics learning sequences.

Towards interactive engagement as a basis for physics curriculum reform

As laid out in a previous paragraph the development of concept inventories and the awareness this brought about concerning students' difficulties led to a host of curriculum reform initiatives at several universities, especially those where established PER groups had been formed. Unfortunately, many earlier efforts were restricted to mostly 'service' or 'non-mainstream' courses which established physics faculty regarded as 'safe ground' for 'experimenting' with how physics is taught (Etkina, 2012, personal communication). The work of Hake (1998) and his collaborators gave researchers and curriculum designers much confidence in being able to back up their claims with statistical rigour. The efficacy and value of the interventions they had developed could be tested and verified.

In Section 2.3.1 the emergence of *interactive engagement* as the overarching philosophy driving reform was discussed—see also the more recent report by Freeman et al. (2014) confirming the efficacy of *active learning* in STEM subjects. A more comprehensive review of research on active learning as a basis for instruction in physics was done by Meltzer & Thornton (2012). Redish's book *Teaching Physics with the Physics Suite* gives an overview of several "research-based" instructional strategies, curricula, materials and assessments and proposes a context driven system (the "Physics Suite") for rolling out its "elements" (Redish, 2003b, p. 3). In this section, only some of the most notable works and outputs will be mentioned again to provide a picture of what PER has accomplished.

Peer Instruction (Mazur, 1997) has been one of the more influential resources targeting reform in how lecturers communicated with their students. No longer was the lecturer seen to be the source of knowledge, but concepts were to be actively engaged with and constructed by students – see Crouch & Mazur (2001), and Crouch, Watkins, Fagen, & Mazur (2007), for appraisals of the method over the years subsequent to its introduction. Analysing student responses to a sequence of conceptual questions, a well-known team of PER researchers led by Carl Weiman at the University of Colorado-Boulder concluded that peer instruction is effective in achieving gains in understanding, even in cases where none of the students at first had correct ones (M. K. Smith et al., 2009). Other lecture-based methods developed as a result of PER work include *Interactive Lecture Demonstrations* (ILDs) (Sokoloff & Thornton, 2006), which draws on CADAA[20] and worksheets to get students actively engaged in lectures. *Just-in-Time Teaching* (JiTT), developed by Novak and his collaborators, employs a combination of modified lectures, group-discussion problem solving and web technology (Novak, Patterson, Gavrin, & Christian, 1999).

For recitations or tutorials, the UWPEG proposed a model for reform, *Tutorials in Introductory Physics* (McDermott et al., 2002). The same team at the University of Washington also introduced *Physics by Inquiry* (PbI), a laboratory-based approach flowing directly from work on student misconceptions (McDermott & UWPEG, 1996a, 1996b). The *Investigative Science Learning Environment* (ISLE) developed at Rutgers University is built around the constructivist view that students can only come to fully understand scientific concepts if they discover them for themselves (Etkina & Van Heuvelen, 2007). This model for running a physics course is centred around an iterative process whereby students first have to observe and/or explore phenomena. They then get time to construct explanations for what they observe, for which they formulate hypotheses and 'self-design' experiments to test the accuracy of their explanations. Equipment and guidelines are provided so these experiments are not completely open-ended. Through a cycle of testing and refining, students get an opportunity to establish and apply scientific principles and use

[20] Note that CADAA is an essential part of *probeware* – see earlier discussion in Section 2.3.1.

the results to solve problems, and finally explain and update their knowledge state. The 'ISLE cycle' is an approach which may be compared with the 'predict-observe-explain' (POE) cycle postulated by the science education researchers (White & Gunstone, 2014). The final step involves resolving any conflicts between predictions and observation. The same team of researchers produced the *Physics Active Learning Guide* (Van Heuvelen & Etkina, 2006). *Cooperative problem solving* (CPS), developed by the Hellers and their collaborators at the University of Minnesota (Heller & Hollabaugh, 1992; Heller, Keith, & Anderson, 1992), is grounded on the studies by the Johnsons that showed the effectiveness of structured group learning (Johnson & Johnson, 2009). CPS uses context rich problems which students have not seen before. *Real Time Physics* (RTP) (Sokoloff et al., 2011), drawing on CADAA and knowledge of student conceptual difficulties, is a laboratory approach that uses technology and cognitive conflict to help students build concepts. RTP was designed to be used in traditional lecture/laboratory/recitation teaching environments.

Some approaches blend a range of strategies, whereas others have attempted to reform the entire classroom, such as workshop or studio methods wherein lectures are totally eschewed in favour of sessions working with physics devices and assistive teaching materials). PbI, described in a preceding paragraph, was possibly the first full "guided-discovery" laboratory-based program that departed radically from the traditional physics laboratory experience of "cookbook labs". The philosophy of the approach is that student meaning-making about the physical world is more important than 'surface learning' a host of physics topics. *Studio Physics* (SP) or the '*Comprehensive Unified Physics Learning Environment*' (CUPLE) (Wilson & Redish, 1992; Wilson, Redish, & Donnelly, 1992) and SCALE-UP (Beichner et al., 2007), both also utilise a workshop or studio type teaching environment. SCALE-UP is a flexible and highly interactive classroom setup that leverages group work, lecturer instruction, immediate feedback, computer technology and other tools in a synergistic way to facilitate and enhance both student-student and lecturer-student interactions. *Workshop Physics* (WP) developed by Laws and her collaborators at Dickinson College (Laws, 1991, 2004) is often touted as an exemplary model for developing teaching tools and techniques in an iterative 'research-evaluate-develop' cycle involving physicists, engineers and computer professionals working to the same goal.

Arons' book, *A Guide to Introductory Physics Teaching* (Arons, 1990), is an instructional tool that summarises the findings of the first few decades of PER especially in terms of students' learning of concepts and their reasoning. It provides useful suggestions for teaching specific topics. This resource has had a major impact on mainstream physicists becoming aware of student difficulties with conceptual understanding—for example, Hammer et al. (2005) leverages this work in their development of the now well-known cognitively-oriented resources framework for transfer in physics learning. Knight's *Five*

Easy Lessons: Strategies for Successful Physics Teaching is yet another example of a 'manual-type' resource book for the application of PER to the physics classroom across a wide range of topics (Knight, 2004a).

In summary, work in the area of reforming curricula and developing instructional tools has led to the adoption of active learning tools within interactive engagement teaching strategies to address student difficulties. This represented a paradigm shift for many traditional physics university courses; whereas before, the focus was on the brilliance and teaching skill of the expert physicist *cum* educator, now in essence the focus has shifted to the student. For a comprehensive review of research on active-learning instruction in physics, see the resource letter by (Meltzer & Thornton, 2012).

But, if we focus on the student, especially how students learn new physics, what should researchers and educators focus on? The following sections chronicle the various ways in which the PER community have conceptualised what is important in students learning physics, as relevant for the thesis.

2.3.3. Problems with physics problem solving

As previously discussed, problem solving was one of the earliest and primary drivers of PER. In the physics community, being proficient in problem solving is deemed a necessary attribute of a qualified and competent physicist (see for example Docktor & Mestre, 2014, p. 6). The PER review by Maloney (2011) and the resource letter by Hsu, Brewe, Foster, & Harper (2004) are both examples of literature on research focusing on problem solving in physics.

Alan Van Heuvelen (1991a), in what is regarded as a seminal piece of work in PER, *Learning to think like a physicist,* suggested a strategic approach to solving problems with multiple representations that mimicked the way in which physics experts solved problems. Expert physicists carefully model physics problems in order to gain a better understanding of the system at hand. Many physics educators and researchers have translated these findings into first cataloguing and then teaching physics experts' problem-solving procedures to students. For extensive reviews of the expert-novice dichotomy around the achievement of proficiency in physics problem solving, see Maloney (2011).

But what constitutes good problem solving, or from the interest of the physics educator, what specific problem-solving aptitudes must be either developed or specifically taught to students? The rubric developed and validated by Docktor (2009) in her PhD thesis, and later expanded upon in a full publication (Docktor et al., 2016), provides a number of processes which may be taken as problem-solving steps.

The team at Rutgers, leveraging the work of Van Heuvelen (1991a, 1991b), developed a four-step strategic approach to physics problem solving resulting in the non-calculus textbook *College Physics: explore and apply* (2nd edition by Etkina, Planinsic, & Van Heuvelen, 2019). The *Physics Active Learning*

Guide (Van Heuvelen & Etkina, 2006) is a textbook aid for students, developed and refined by the Rutgers team over the years and its worksheets and exercises put this philosophy into effect. This kind of strategic approach to problem solving has also been adopted and developed by Knight in his calculus-based textbook, *Physics for scientists and engineers: A strategic approach* (Knight, 2004b).

Van Heuvelen (1995) argued that *experiment problems* in introductory physics labs could assist in helping students develop the more advanced skills required to solve real-world problems in their post-study careers. One expert-like physics problem-solving skill is to represent physical processes in multiple ways—physics lecturers are fond of saying to their students that they must "learn how to *model* the problem". To help students develop a deeper appreciation for the role of representations in solving problems, Van Heuvelen & Maloney (1999) provide a tantalising and fun solution. Based on their many years of experience teaching problem solving at the introductory university levels, corroborated by colleagues and PER research, they suggest that a focus on a one-directional, multiple-representational strategy is not enough to foster expert-like practices in students. Students need to adopt more flexible (and *reflexive*) strategies for solving physics problems.

Lately, in PER, there is a renewed interest in "mathematisation"[21] in physics—the theme of the recent 2017 AAPT summer meeting and PERC held in Cincinnati, Ohio, USA. Despite the best efforts of university physics educators—expounded on in the preceding sections—, students still exhibit serious shortcomings in their understanding of the physics concepts elucidated by the representational forms of mathematics. Of course, in most problem-solving tasks in physics, proficiency in working with mathematical resources is key. In a recent work, Eichenlaub & Redish (2019) set out a contemporary view in PER of how to "blend" physics with "mathematical form" in physics problem solving. Importantly, they state, in the first sentence of that paper, "*Physicists and educators have long held problem solving to be one of the key tools to help students understand physics"* (p. 1). Blending the development of conceptual mathematical understanding with the learning of new physics is an important issue for this thesis, as it speaks to the multiplicity of representational use in physics—see Chapter 3.

It seems clear from the literature that improving problem-solving performance goes hand in hand with the simultaneous use of alternative problem types *and* reformed instructional strategies—as an example, see Heller & Hollabaugh (1992).

[21] "Mathematisation is defined by the editors of the 2017 PERC Proceedings as, "the spontaneous tendency to use mathematical concepts to quantify and make sense of the physical world. It is not about how well people can perform mathematical procedures. Rather, mathematization describes how people conceptualize the meaning of mathematics in the context of physics" ("2017 Physics Education Research Conference Proceedings Details Page," n.d.)

Research into the use and functioning of representations in physics played an important role in condensing the strategic problem-solving approach. The particular meaning-making and communication functions of representations in physics work will be explored in more detail in Chapter 3.

As alluded to earlier, early PER work was mostly conducted by 'pure' physicists, so the statistical rigour of the methods used in cognitive psychology naturally appealed to these researchers—it was a good fit for PER's earlier leading scholars who were almost all exclusively 'pure' physicists before becoming interested in how to better understand and assist how their students learn new physics knowledge. It is now opportune to reflect on the contributions and perspectives from non-American scholars, and from fields of human inquiry outside of physics education.

2.4. Perspectives from non-American regions, science education and philosophy of science

In PER, a relatively new but maturing sub-field of physics, we are interested in how physics knowledge is constituted, and how best to provide answers to the educational challenges of lecturers and learners in coming to grips with the discipline's ideas and praxes—its ways of knowing and doing.

Over the last few decades research in the scientific community around the development of conceptual, theoretical and analytical frameworks has provided a large contribution to the 'language' used to inform science teaching and learning.

Relevant for this thesis is a discussion of what constitutes knowledge in the domain of science, and specifically physics. As a placeholder for the author's own thinking around what physics in essence is about, the following quote seems apt:

> Science is not just a collection of laws, a catalogue of unrelated facts. It is a creation of the human mind, with its freely *invented ideas* and *concepts*. Physical theories try to form a picture of reality and to establish its connections with the wide *world of sense impressions*. [emphases added]
>
> (Einstein & Infeld, 1938, p. 310)

In this thesis the usage of the term *real-world phenomena* refers to this world of sense impressions, and usage of *physics concepts* specifically refers to the expression of formalised disciplinary concepts through the specialised 'language'—explained in more detail in Chapter 3—developed by the discipline. So, learning about physical theories must involve connecting real-world experiences of phenomena to the formalised concepts. When students are learning conceptions that are in line with those held by the physics community, it therefore makes sense to leverage and pay attention to how students will naturally conceptualise their experiences within their pre-existing world view. This is why it is appropriate to approach pedagogy with an awareness of providing tools and other resources, not necessarily used in the discipline, to make content accessible for students—explained in more detail in Chapter 3.

Lemke, another physicist turned education researcher, added significantly to the discussion about the nature of science and how scientific discourses are constructed. Critically, he challenged the belief that cognitive or mental approaches to learning, focusing purely on understanding and concepts, could provide a full picture to inform better teaching in science. He argued for attention in teaching to all the modes of scientific discourse—language, symbols, images, actions, etc. Instead of speculating on what is going on in students' brains, he framed science teaching as enculturating learners to the "very specific and often specialized forms of human activity", i.e. a focus on what students *do* in discourse practices, and "using particular ways of making meaning about natural and technological phenomena"—see Lemke (1998).

Lemke explains his reasoning for adopting a social semiotic perspective as follows:

> The natural language of science is a synergistic integration of words, diagrams, pictures, graphs, maps, equations, tables, charts, and other forms of visual and mathematical expression.
>
> Lemke (1998, p. 6)

So, for Lemke, science is constituted of a 'multiplicity of languages'. Further, he argues that success in teaching science should be gauged by how well students are able to integrate all these 'languages' "*[...] in meaningful and appropriate ways, and, above all, to be able to functionally integrate them in the conduct of scientific activity.*" We see here also the social dimension of meaning-making in scientific work. This thesis contributes to such an exploration into the roles of all the languages in the discourse practices of physics, aiming to contribute to the PER literature on

This thesis contributes to such an exploration into the roles of all the languages in the discourse of physics.

For a thesis such as this, situated within PER, it is appropriate to reflect on the immense impact that non-American PER and science education (SE) research have had on especially the development of conceptual, theoretical and analytical frameworks. Over the last few decades the results from the discussions in the scientific community around these perspectives have provided a significant proportion of the 'language' to talk about matters around science teaching and learning. However, at best, this can only be a cursory overview, as the wealth of studies is overwhelming and often contradictory—for example, much of European SE takes as starting points theories of thinking developed within the social sciences, where it is completely acceptable to have a wider net of knowledge genesis. Instead, this thesis pragmatically only ‘dips’ into areas that are fruitful for the study described, or to support accepted notions within PER. This section is not exclusively reserved for non-American contributions, but rather a reflection on the influences that has informed the development of the author’s framing of the conceptual framework used in this study—see Chapter 3. This is humbly done from the vantage point of a scholar just scraping the surface of the body of available knowledge and one which is constantly being updated and refined.

Kuhn was an American philosopher of science. Which physics educator is not familiar with the term ‘paradigm shift’? His seminal book, *The Structure of Scientific Revolutions* (Kuhn, 2012), is often quoted by researchers in science education who are interested in the structure and nature of scientific knowledge. Kuhn highlights the unique nature of science which distinguishes it from other disciplines. It is as if the sciences subvert the ‘messy’ historical details of the development of canonical facts and ideas which have survived cycles of rigorous testing and refinements. Moreover, purified knowledge statements are then deposited into textbooks and other scientific artefacts (devices, tools and procedures, computer code), which, akin to perhaps only theology, provide consistent and coherent reference works for working in specific fields. Students are then expected to use these books as manuals for learning the established ways of knowing, which the community of scientists have decided are salient for different topics. In the light of this, it is therefore not unreasonable to find xpect that the science students often will find it difficult to fathom what ‘scientific thinking’ actually entails. If the development of scientific ideas which established the knowledge students are supposed to use proficiently in disciplinary tasks are so hidden, how are they supposed to construct new scientific ideas for themselves in appropriate ways, as education literature suggests?

Another great influence on past and contemporary thinking around educational approaches is that of the work of the Russian psychologist Lev Vygotsky—his seminal works were compiled by friends after his death in 1934, and are often referenced in science education articles, most notably, *Thought and Language* (Vygotsky, 1962). For the purposes of this review, it is expedient just to touch on a few of the ideas that have made such a significant impact on the work of earlier and current researchers in the fields of educational development.

Vygotskian thinking argues that authentic cognitive development can only be attained by full social interaction with more knowledgeable peers and teachers in an interaction space called the “zone of proximal development” (ZPD), arguably one of the most used and applied theories in learning studies and childhood development. This is in contrast to Piagetian thought where learning is mostly an internal (inside the human brain) process. Vygotsky can thus be considered the father of the socio-cultural perspective on learning. Of course, what exactly constitutes an optimal ZPD for a particular individual in a specific context, in learning a certain skill or idea, depends on affective factors, e.g. the individual learner's motivation and sociability. Many researchers have termed the teaching style of creating appropriate ZPDs for students as *scaffolding* (for just a couple of examples of groups using this idea in PER, see Lin & Singh, 2015, and Maries, Lin, & Singh, 2017; as well as Lindstrøm & Sharma, 2011). Not surprisingly, many of the ideas from Vygotsky's work have become the overarching principles which form key tenets of constructivism.

SE research and PER had a shared genesis, as discussed in the first section of this chapter. With Sputnik and the space race which started in the late 1950s, it was not only physics, engineering and mathematics education that enjoyed renewed attention. Whereas PER developed into a mostly university-focused endeavour, science education research was primarily attending to secondary school science. In addition, science education, despite various theoretical explorations, was (and still is) mainly focused on the naturalistic, experimentalist paradigm of scientific inquiry. Notwithstanding, theoretical frameworks have driven the research interests of SE. De Jong (2007) describes three waves of innovation coupled to three major shifts in thinking about what matters in developing effective science curricula for schools.

Initially, the underlying theme was on identifying proven approaches which could best stimulate the types of thinking and behaviours deemed critical for young scientists. Naturally these were aligned to the interests of the SE research community. De Jong characterises the first wave (1960s to 1980s) as grounded in two psychological theories; *descriptive behaviourism* (based on the work of B. F. Skinner)—which led to a focus on direct-feedback tasks and the development of multiple-choice questions to assess learning outcomes—, and *cognitive development* (see preceding sections, especially the discussion on Piagetian perspectives)—this affected how topics were sequenced in curricula and textbooks. Evidence started mounting that science students were not adopting the behaviours of scientists, so a second wave (1980s -2000s) washed in new ideas from *cognitive psychology* (see preceding sections) and *information-processing.* The third wave (2000s to present) brought in an awareness that learning in science is best done in a community of practice, formed from research based on *social constructivist* and *socio-cultural* perspectives.

In SE, there has been a great amount of work in the area of students' conceptions of science—early work by Gilbert & Watts (1983), Driver (1989) and other scholars represent some of the earlier interest in this important research area for science teaching and learning. Much has already been written in this chapter on conceptual understanding, and the underlying questions which cognitive perspectives added to the area. Suffice at this point to simply point to some of the more influential works in the area of science education research.

A lot of effort has gone into problematising students', teachers', and trainee-teachers' alternative conceptions about science—for early examples, see Gilbert & Pope (1986), who used a case study research approach in small group discussions, and Aguirre, Haggerty, & Linder (1990) who looked into student-teachers' conceptions also employing a case study approach. What emerged from this body of research was a concomitant commitment to effecting *conceptual change* towards more appropriate understandings of science concepts, predicated upon constructivist science teaching methods—see for example D. E. Brown & Clement (1989), Duit & Treagust (2003), Posner et al. (1982), and R. T. White & Gunstone (1989). However, a number of scholars have challenged this notion. Linder (1993) argued that context is indispensable when considering science learners' conceptions, and argues instead for developing student's capabilities to distinguish between conceptualisations. In a similar vein, Mortimer (1995) argues for "conceptual profile change" rather than conceptual change. The notion in both examples is that forming disciplinary-appropriate concepts about science should be seen as a process towards greater flexibility power and contextual precision, rather than replacing existing ones.

In the Swedish science education research arena, Ference Marton and Roger Säljö (1976), taking a socio-cultural perspective on learning, first identified *surface-level* and *deep-level* processing. Deep learning essentially involves understanding in which students engage in "on-line theorising", whereas surface learning is by rote, with students only referring to basic factual and procedural information (Chin & Brown, 2000). Case & Marshall (2004), in a study with second year South African chemical engineering students, identified two context dependent 'transitional' approaches that students use when solving problems—either 'procedural surface' (algorithmic) or 'procedural deep'. From the perspective of the student trying to pass a course, these approaches could be classified as 'strategic' approaches, both being potential blockages to the hoped for deeper learning of concepts. The importance of their findings for task design is: even carefully structured tasks for which students are explicitly taught strategies may not be enough to assist some students learning and understanding the underlying concepts.

A *social semiotic* view of science learning is central to the conceptual framework for this thesis, as this approach lends itself to the language needed to discuss the movement of meanings between multiple representations, which are seen as components of additional 'languages' of science. Physicists and PER's should start by first understanding what it is that students have to know in order to bring about a better awareness of how the physics community as a social group make their meanings. What we want to explore as PERs is how learning works in practice in physics, and then how this can inform teaching and learning efforts in physics in general.

The *Variation Theory of Learning* (VTL) as championed by Marton and Booth (see for example, Marton & Booth, 1997) is another important contribution from European Science education theorists. The main concepts underscoring the work in this thesis will be laid out in Chapter 3. For now, it is germane to point out that this way of framing science learning is very useful to connect the cognitive perspectives referred to so far and the social learning spaces students are exposed to in the science classroom.

2.5. Situating this study

2.5.1. A historical map of PER

Figure 2.1 offers a condensed timeline which summarises the key milestones of the development of physics education research. Using this timeline, it is possible to identify three major eras in the development of PER. The first phase represented organising work, in which various initiatives purposed to improve science schooling; by this time several universities and government agencies started reserving significant portions of their budgets to curriculum development and training. Then, by the late 1950s PER proper started, with many physicists at university physics departments deciding to redirect their careers to improving the learning of their students. The advent of the microcomputer coincided with the idea of using real-time data acquisition for educational purposes—the era of *microcomputer-based laboratories* (MBL) arrived for which the express purpose was to create for students hands-on learning experiences with which they could connect experiments with the abstract representation of the data (Tinker, 2000)[22].As evidence started coming in about students' lack of understanding of basic physics concepts, a greater attention to learning theories (1990s to present) marks the start of the modern era.

[22] A good review of MBL (or *probeware*) may be found in (Euler, 2020).

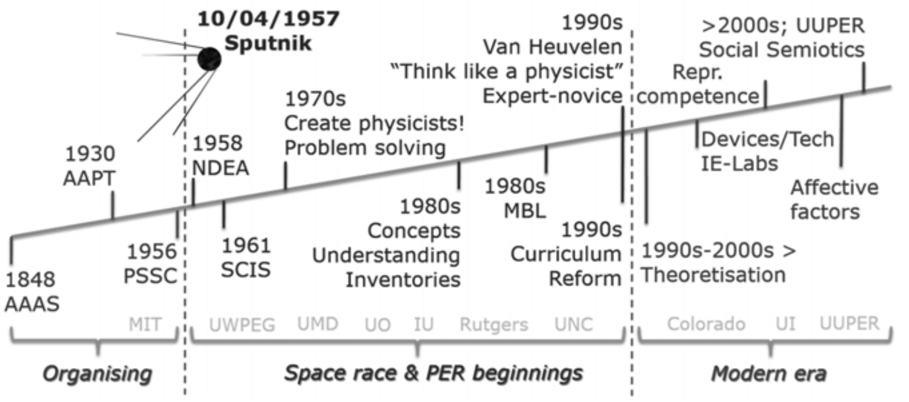


Figure 2.1. Major milestones of PER. Acronyms on the bottom refer to university groups.

2.5.2. Representations in PER

In Figure 2.1 the work of Van Heuvelen is placed at the end of the birth period of PER, and at the cusp of the modern era. This is done to signal what has become, for my research, a watershed moment of work on representations, and today is a much-studied aspect of scientific work and learning how to become competent in doing physics (or science in general). Research into the role of representations in physics has played a major role in PER work, and this thesis is solidly situated within that branch. Work in the area of representations has greatly added to the conceptual framework for the thesis. This section is an attempt to summarise and collate work on representations, as a precursor for the discussion in Chapter 3; further elaboration is then provided in Chapters 4 and 6.

The earlier strategic approaches to problem solving—students move in a sequential manner through the modelling and solution of a problem in clearly defined steps—using a multiplicity of representations (diagrams, graphs, mathematical equations, physics-specific verbal descriptions) may be characterised as a 'fixed' approach to physics problem solving.

However, a series of studies have shown that it is the 'backwards' and 'forwards' nature of working with multiple representations that more completely describes how experts use representations, and that learning becomes possible when students are actively engaged in moving meanings *between* the representations (Dufresne, Gerace, & Leonard, 1997; Kohl & Finkelstein, 2008; Kohl, Rosengrant, & Finkelstein, 2007; Meltzer, 2005; Rosengrant, Etkina, & Van Heuvelen, 2007; Van Heuvelen & Zou, 2001). As mentioned in Section 2.3.3, the *Active Learning Guide* (Van Heuvelen & Etkina, 2006) is a physics textbook aid designed around this principle.

Instead of simply learning the physics content (or ‘theory’), working with multiple representations and gaining *representational competence* have become the focus of much work in PER (for example, see Kohl & Finkelstein, 2005). Some research in PER has studied the effect of various *representational format* on problem-solving performance (Kohl & Finkelstein, 2006b; Meltzer, 2002, 2005). Kohl & Finkelstein (2006a) showed that students enrolled in a “reform-type” course, i.e. one employing interactive engagement, displayed more expansive use of multiple representations. One of the aspects of the conceptual framework developed for this thesis attempts to build on these perspectives, and will therefore be discussed in a more comprehensive way in Chapter 3.

2.5.3. Mathematisation in PER

The mathematisation dimension of physics problem solving was briefly discussed in Sections 1.1.1 and 2.3.3. Folding in the development of conceptual mathematical understanding with the learning of new physics is an important issue for this thesis, as it speaks to the multiplicity of representational use in physics and will therefore be discussed further in Section 3.3 of Chapter 3 which sets out my conceptual framework.

2.5.4. Interactive engagement with probeware

The active learning approaches developed in PER (Section 2.3), and their reported success and ever-wider adoption, resulted in physics faculty starting to appreciate that you learn well when you interact with others. Probeware tools have proven themselves to be vehicles for promoting active learning with students especially if they are incorporated with interactive engagement strategies—see the preceding sections for the full discussion in this regard.

A probeware tool, the iOLab, therefore offered the possibility of designing active learning scenarios. More specifically, this single probeware tool seemed to epitomise this class of physics tools—a “shoebox” device loaded with a host of sensors to do physics[23], and real-time updating of displayed information, to allow students direct experience of phenomena. By applying a social semiotic lens (described in Section 3.4), this thesis investigates the role of probeware tools within interactive engagement laboratory settings so that there may be a better understanding of why and under what circumstances these tools may be effective.

[23] A dream expressed by John King (1966), long before these types of devices became available.

2.5.5. A theoretical evolution map of PER

Figure 2.2 recounts the development of theoretical perspectives in PER. With the initial focus on developing new and better curricula aimed at producing more physicists, the starting period of PER may be characterised as having an atheoretical genesis. However, as researchers were trying to come to grips with their students' lack of appropriate understandings of key physics concepts, cognitive perspectives informed the early theoretical approaches. Over time various aspects and theoretical approaches from other fields of human inquiry were beginning to be explored within PER. Meltzer and Otero (2015) have published an article that briefly sets out the history of PER in the USA, stretching from 1860–2014. There are a couple of unanswered questions in PER they identified which this thesis may shed some light on. They ponder why there seems to be great difficulty in implementing, in a sustainable way, teaching methods supported by research ("inquiry-based", scientific practices"), and whether modern PER's focus on students' understanding of physics concepts can lead to sustainable educational reform. By addressing the 'multimodal' nature of students learning in IE settings I hope that my research can add to the current knowledge state of what constitutes effective learning of new physics concepts for students.

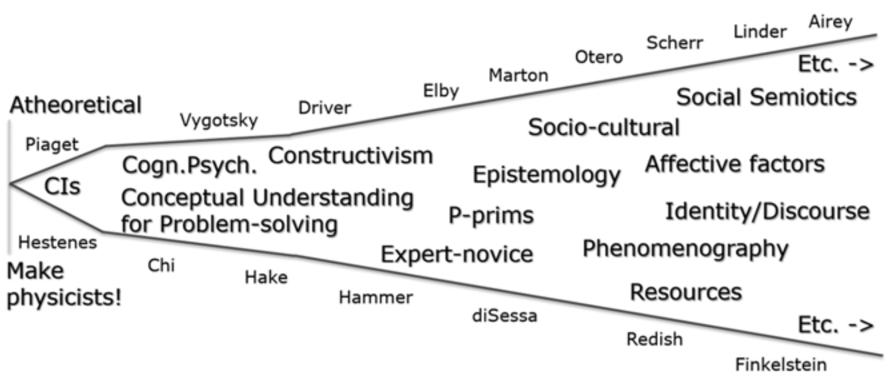


Figure 2.2. An expansion map of theoretical perspectives in PER, loosely arranged in terms of time progression from left to right. The names on the outside of the 'cone' are the more influential contributors.

The findings from PER described in this literature review point to the effectiveness of interactive engagement as the one sure vehicle by which students tend to develop better problem-solving skills. But, as stated previously, there is significant work still to be done in figuring out what works in various contexts and why. To investigate these questions, I have chosen a conceptual framework that incorporates various elements which have their roots in *social semiotics*. This approach will be explained in the next chapter.

This chapter has discussed the historical development of the (mainly North American) PER community. This was done to set the backdrop for this thesis. In doing so issues of representation in physics have purposely not been discussed. This is because this is the main area of research to which this thesis contributes. As such, the next chapter (conceptual framework) presents a picture of research in the area of physics representations and the main theoretical underpinnings upon which this thesis is based.

3. Conceptual framework

In this chapter, I present a *conceptual framework* overview. By that I mean an overview of the "system of concepts, assumptions, expectations, beliefs, and theories" (Maxwell, 2013, p. 39) that I have built my thesis work on. By constituting the chapter in this way, the intention is to provide an interwoven description that, together with the Chapter 2 literature review, positions my methodology and research questions as new contributions to the field of PER in a valuable way.

3.1. Introduction

Theoretically and methodologically my thesis is grounded in a *multimodal social semiotic* perspective. As such, it is about how I have made sense of the social semiotic parts that go into making up the perspective. There are four important parts on which I built my conceptual framing.

Firstly, it is my experience as a physics teacher and my commitment to making learning possible (as described in the Preface).

Secondly, the work of Jay Lemke, a theoretical physicist who became internationally recognised as a semiotician and who started to become well known to the physics education community after publishing the seminal book, *Talking Science: Language, Learning, and Values* (Lemke, 1990). Using physics examples, Lemke has repeatedly illustrated how the communicative practices of physics require coordinating meanings that are formulated using one or more semiotic system. These semiotic systems are the "modes" in the multimodal social semiotics of my conceptual framework. Perhaps the most important part of Lemke's work for my thesis is how he presented the case that the use of only one semiotic system to share meaning is rare in the discipline of physics. Almost always, several are used simultaneously. For example, consider the combinations of linguistic, mathematical, and pictorial semiotic systems that are used in textbooks and research presentations and publications. In this respect, Lemke made this fundamental observation: It is not as if the semiotic systems that are used are "redundant" in that each system is capable of presenting "complete relevant information in a different medium". Rather, it is the "nature of the genre" to require "close and constant integration and cross-contextualisation" amongst the semiotic systems that get used to make meanings (Lemke, 2004, p. 194). Put simply, each semiotic system represents different aspects of the same phenomenon.

Thirdly, the ground-breaking work in the area of representations done by the PER group at Rutgers. For me, this work shifted the meaning of representation in the field of PER from a positivist one-to-one unproblematic representation of phenomena to that of a number of semiotic resources that are used for meaning-making. In particular, (a) the examples given in Alan van Heuvelen's (1991) paper entitled *Overview, Case Study Physics*, which vividly demonstrated the Lemke case just cited. And (b) the extrapolation of *Overview, Case Study Physics* by Eugenia Etkina and Alan van Heuvelen into a view of active learning (Van Heuvelen & Etkina, 2006) that I went on to use extensively and productively in my physics teaching. Then in 2006, David Brooks presented a PER PhD that showed both the acceptability and value of making a theoretical semiotic contribution to the field of PER as an integral part of his PhD work (Brookes, 2006).

The fourth point of departure for my conceptual framing comes from the research work done by the Uppsala University PER group during the past 15 years (see Section 3.4). What the Uppsala group did is combine the social semiotic approach to communication formulated by Gunther Kress and his colleagues at the Institute of Education at University College in London—for a direct example, see Kress (2010), and for many associated examples, see Jewitt (2017)—with the existing representational work in PER. In so doing, the Uppsala group formulated a coherent web of new constructs that allow new ways of thinking and talking about semiotic resource systems in a physics education context. Of particular relevance to the development of my conceptual framing was the proposal that the social semiotic perspective developed at Uppsala could be used to fruitfully recognise learning as it took place in interactive laboratory settings (also see Kress, 2013; Kress, Jewitt, Ogborn, & Tsatsarelis, 2014).

From here, my research became about investigating the ways in which physics students learn to appropriately interpret and use multimodal semiotic resource systems in interactive student laboratory settings. My conceptual framework facilitated my "interrogation" of the finer details of meaning-making in my chosen research context.

3.2. Modes, multimodality and social semiotics

A mode is "a socially shaped and culturally given semiotic resource for making meaning. *Image, writing, layout, music, gesture, speech, moving image, soundtrack and 3D objects* are examples of modes used in representation and communication." (Kress, 2010, p. 79, emphasis in original). Physics and physics education use a set of particular modes (what I refer to as semiotic resource systems), the most common probably being graphs, mathematics, specialist language, diagrams, and gestures to create its meanings. Multimodality is a term used to collectively characterise modes in relation to an understanding that communication, and how that communication is formulated, is much more than just the language that is used. As such, multimodality is a field of study that gives explicit attention "to the full range of communicational forms people use—image, gesture, gaze, posture, and so on—and the relationships between these" (Jewitt, 2017, p. 15). On the other side of the coin, social semiotics "is the theory with which [multimodality] is approached". How multimodality and social semiotics fit together is that "modes shape our encounter with the world and our means of re-making the world in semiotic entities of any kind." (Airey, 2016; Kress, 2011, p. 46; Kress et al., 2014).

As such, social semiotics provides a researcher with the kind of theory needed to examine how a particular social group communicatively shares meaning. For my work, the social group of interest is made up of everyone involved in undergraduate physics education. As pointed out in the introduction to this chapter and earlier in this section, physics and physics education uses a set of particular modes (semiotic resource systems), to create and share its meanings. However, what a mode is, is elusive because different social groups see what constitutes a mode differently. The social group making up the music video industry could arguably have image, 3-dimensionality, layout, colour, clothing and music as their principal modes. However, in both the physics and the music video industry cases, what is regarded as a mode is also a semiotic resource system. That is, a system used for meaning-making. Hence, my preference for using this terminology for the "socially shaped" and physics-situated semiotic resources developed and used for making and sharing meaning (this is expanded upon in Sections 3.2.3).

3.2.1. Agency in social semiotics

Much of the contemporary work done in social semiotics seeks to analyse the ways in which language and other forms of representation are used in societal communication to make the meanings deemed important for those communities (Jewitt et al., 2016; Kress & Van Leeuwen, 2006). It is understandable then that social semiotics is often related to the perpetuation of power structures. Indeed, for some, social semiotics has become synonymous with a critique of such power structures—see, for example, Hodge & Kress (1997).

In this thesis, I make no attempt to leverage social semiotics to critique the meaning-making practices of expert physicists or the power structures they may represent. This does not mean that I am uninterested in issues related to the agency of university students—far from it. However, such a research thread would involve a very different set of studies, for, as Butler (1997) points out, for physics students the paradox of achieving agency lies in submitting themselves to a discourse they themselves had no part in creating.

3.2.2. Language as one amongst many modes

Multimodal social semiotics (MMS) has its roots in Halliday's (1978) work in the field of semiotics in which he developed a framework for studying the meaning-making functions of language (chiefly English)—called *systemic functional linguistics* (SFL) (Halliday, 1985).

Over the following decades SFL became a well-developed explanatory system and linguists began to turn their interest to studying the contribution of so-called extra-linguistic 'modes' (such as gestures and images) to meaning-making using the same SFL constructs. Here the work of Kress was seminal. Together with Van Leeuwen, Kress developed a specialised grammar for reading images (Kress & Van Leeuwen, 2006). Kress and Van Leeuwen's work is important because it led to the development of the field of *multimodality* (Goodwin, 2000; Kress, Jewitt, Ogborn, & Tsatsarelis, 2001). In this perspective, language was no longer seen as the main bearer of meaning with a number of extra-linguistic modes added as necessary; rather, each mode or semiotic resource system became viewed as having different *affordances*, that is *different potentials for representing or making meanings,* for example, in the science classroom:

> 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?"
>
> (Kress et al., 2001, p. 1)

This shift to a multimodal view of meaning-making generated interest amongst scholars from fields as diverse as science education and multimedia studies. Today multimodality is a rapidly growing field of research (for example, it was the theme for the 2019 AERA[24] annual meeting). Leading scholars in the field have recently attempted to condense, from a wide range of research traditions, three core premises that characterise multimodal research in general:

> 1. Meaning is made with different semiotic resources, each offering distinct potentialities and limitations.
> 2. Meaning-making involves the production of multiple wholes.
> 3. If we want to study meaning, we need to attend to all semiotic resources being used to make a complete whole.
>
> (Jewitt et al., 2016, p. 3)

[24] The American Educational Research Association.

3.2.3. Clarifying the use of terminology

At the end of the introductory paragraphs of Section 3.2, I pointed out that I was choosing to use the terminology *semiotic resource system* rather than *mode*. I now expand upon this choice. In cognitive psychology, the term *mode* has a direct link to the human senses—sight, sound, touch, smell, and taste (with the overwhelming majority of work focussing on sight and sound). Linguists, however, have broken this link to the senses and use the term *mode* to describe any self-sufficient meaning-bearing system—principally springing from the work of Michael Halliday (1978). Thus, for linguists, graphs, diagrams and written language are treated as separate modes even though they are all visual resources (for example, Halliday, 1993). In order to define what can and cannot be a mode, Kress & Van Leeuwen (2006) suggested that three 'metafunctions' of a system could be identified; these are the *interpersonal*, *ideational* and *textual* meaning-making functions. In order to qualify as a mode, it was suggested that a semiotic meaning-making system would need to possess all three metafunctions.

Whereas there is broad use of this definition in the field, it is not without its critics. Doran (2018) for one showed that it does not readily apply in mathematics, where the interpersonal[25] metafunction is borrowed from language.

Therefore, to avoid any controversy over its use, instead of 'mode(s)' the term *semiotic resource systems* will be referred to here; with any resource that is used to communicate meaning in physics deemed to belong to a semiotic resource system of one type or another. In this thesis, the term *multimodal* will be used to either draw attention to the range of resource systems in an available ensemble, or to characterise inter-semiotic relations and activity.

3.3. Representations

The second research tradition on which my conceptual framework is built originates in the largely empirical work carried out in PER.

The extensive work on representations in PER, confirms the uniqueness of *individual representational systems*—semiotic resource systems—in making physics-specific meanings.

When engaged in scientific activities, scientists make coordinated use of a wide range of representational systems such as graphs, diagrams, mathematics, specialist language, etc. (for example, see Lemke, 1998). Over time, the various scientific disciplines have assigned particular roles to these semiotic resources so that they now signal key aspects of disciplinary concepts.

[25] The interpersonal metafunction concerns the relation between communicants in a discourse, around issues such as power relations, social status, etc. It fulfills the role of establishing 'interactivity' in any communicative practice.

Significant work in this regard has been undertaken in the specialised language of physics (Airey, 2012; Brookes, 2006; Brookes & Etkina, 2007), diagrams (Rosengrant, Thomson, & Mzoughi, 2009), graphs (Bollen, De Cock, Zuza, Guisasola, & Van Kampen, 2016; Christensen & Thompson, 2012; Ivanjek, Susac, Planinic, Andrasevic, & Milin-Sipus, 2016; McDermott, Rosenquist, & van Zee, 1987), mathematisation (Airey, Lindqvist, & Kung, 2019; Bollen, van Kampen, Baily, Kelly, & De Cock, 2017; Eichenlaub & Redish, 2019; Euler & Gregorcic, 2018; Geyer & Kuske-Janßen, 2019; Govender, 2007; Sherin, 2001; White Brahmia, Olsho, Smith, & Boudreaux, 2020), gesture (Euler, Rådahl, & Gregorcic, 2019; Gregorcic, Planinsic, & Etkina, 2017; Scherr, 2008) and video simulations (U. Eriksson, Linder, Airey, & Redfors, 2014). Representational studies are now also being undertaken in cross-disciplinary contexts—see Samuelsson, Elmgren, & Haglund (2019)[26].

Much of the work, as represented by those cited in the preceding paragraph, is concerned with how these different representational systems contribute to the constitution of physics knowledge in learning contexts and the reported findings often have significant implications for the teaching and learning of physics. This thesis will in particular address mathematisation—briefly discussed in Sections 2.3.3 and 2.6.3—from a conceptual understanding perspective. The semiotic lens discussed in this chapter will be applied to investigate student learning challenges around using abstract mathematical tools to describe phenomena and solve a range of problems in appropriate ways (see Sections 6.2 and 6.3, and Papers I, II, and IV). For a discussion on the challenges students experience with learning about and with coordinate systems, see Section 6.2.1. There mathematisation is discussed from the perspective of disentangling the mathematical concepts needed for physics work.

In order to effectively participate in a disciplinary social group, newcomers to the discipline need to learn how to interpret and use the available semiotic resources in order to make appropriate disciplinary meanings.

For this thesis, it is the inter-semiotic relations and activity (i.e. multimodality) of physics representational work that is of interest. Following on from the work of Van Heuvelen (1991); Airey (2009), Airey & Linder (2009), Dufresne, Gerace, & Leonard (1997), M. Eriksson (2020), U. Eriksson (2014), Fredlund, (2015), Kohl & Finkelstein (2008), Kohl, Rosengrant, & Finkelstein (2007), Rosengrant, Etkina, & van Heuvelen (2007), Svensson, Eriksson, & Pendrill (2020), and Van Heuvelen & Zou (2001) have all made significant contributions to the field. This kind of research is now also emerging in the field of astronomy, for example, U. Eriksson (2019).

The significance of Van Heuvelen's early work is that he argued that in order to learn to think like physicists, students should be taught a problem-

[26] This study is particularly interesting as it investigates the use of an applied engineering tool, the infra-red camera, to illuminate for students concepts of heat.

solving strategy that involves the use of multiple representations, similar to the way expert physicists approach problems (see for example, Van Heuvelen, 2001). This 'backwards and forwards' expert-like strategy of using multiple representations is of relevance to the research reported on in this thesis. There are a number of examples of physics courses that have sought, with some success, to design curricula and course materials that epitomise this; as an exemplary example from the PER community, see Van Heuvelen & Etkina (2006).

In the sciences, outside of physics, there exists a large body of work in the area of representations (for a small sampling, see Gilbert & Treagust, 2009; Lee & Jones, 2018; Stull, Gainer, Padalkar, & Hegarty, 2016). Multiple representational work is now being studied across the sciences—for a recent compendium, see Treagust, Duit, & Fischer (2017). And, as different scientific disciplines have different praxes, the different representational systems play different roles and vary in importance. See also the discussions in Section 3.3.1.

Take for example, diagrams. In biology, they serve mostly to emphasise visual features of the organs and tissues of living organisms, and in ecology, they explain the inter-related nature of complex natural phenomena (see, for instance, Treagust & Tsui, 2013) and in chemistry, they are mostly visual models of chemical structures that are too small to see with the naked eye (for example, Gilbert, 2005).

As one consequence of this differentiation in the 'focal plane' for scientific representations, the different scientific disciplines have developed their own definitions and characterisations of what *representational competence* entails for their respective disciplines.

3.3.1. Representational competence

In this section I am going to look beyond PER and bring in science education. This is because of the current limited work that exists in PER.

In science education, there has been a growing discussion about the role of individual disciplinary-specific semiotic resources. This discussion has often been framed in terms of the development of *representational competence* (see for example, (Airey & Larsson, 2018; Kohl & Finkelstein, 2005; Kozma & Russell, 2005; A. Linder, Airey, Mayaba, & Webb, 2014; Mishra, Clase, Bucklin, & Daniel, 2018; Prain & Tytler, 2012; Scheid, Müller, Hettmannsperger, & Schnotz, 2018).

In physics education, available characterisations in the literature offer little practical guidance on how students' representational competence may be effectively facilitated. However, a number of PER scholars have more recently made attempts to theorise around multi-representational usage in physics, albeit from a cognitive science perspective—the most well-known is the so-called 'resources' framework of Redish (2004). Some scholars have talked about terms such as *representational coherence ability* (Scheid, Müller, Hettmannsperger, & Schnotz, 2019) as an aspect of representational competence. A more detailed discussion may be found in Section 6.4 and Paper V, which give a discussion of representational competence in the graph system for 1-D kinematics.

This thesis hopes to add to our understanding of how laboratory work with multiple representations can develop better understanding of physics concepts, and in particular how it may help develop representational competence. This is relevant since, as noted by Airey (2014), the affordances (potentials to make meaning) of discipline-specific semiotic resources are often *tacit* in physics—students cannot develop the required representational competence if the meaning-making potentials of the semiotic resource systems they are supposed to work with are 'hidden' for them.

3.4. A brief introduction to the UUPER social semiotic theoretical framework

In this section I present the theoretical framework underpinning my thesis. The major contributions to this framework have emerged from physics education research undertaken at Uppsala University over the past fifteen years in the field of multimodal semiotics and representations. A recent book chapter summarises UUPER's contributions to this work up to 2017 (Airey & Linder, 2017), which is essentially based on the work of three PhD students (Airey, 2009; U. Eriksson, 2014; Fredlund, 2015). Aspects of direct relevance for this thesis is described below.

It needs to be noted that there are three main differences between the UUPER theoretical framework and other representational work in PER. Firstly, the UUPER framework concerns itself with *group meaning-making*. Put simply, the framework deals with the meanings that have been assigned to disciplinary-accepted semiotic resources by physicists. These disciplinary affordances are discussed further in this chapter in Section 3.4.4.

Secondly, in authentic open-ended laboratory tasks, students are likely to use resources that would not normally be defined as representations—such as laboratory work and physical apparatus. With a focus on multimodality, *all forms of meaning-making* are taken into account and it is often not possible to say exactly what is being represented by a given resource—rather it is a part of a flow of meaning towards a multimodal whole. Thus, the focus in the UUPER framework is on what meaning the resource can convey to students, rather than a question about what the resource itself represents.

Thirdly, within social semiotics, any individual semiotic resource typically has a *range of possible meaning potentials* (Airey, 2014). The key concept here is that each disciplinary-specific semiotic resource has been assigned a set of *disciplinary-specific meaning potentials* and that students need to know which meaning potential is typically leveraged in a particular context. An immediate consequence of this perspective is that students must come to understand *which* meaning potentials of semiotic resources need to be drawn upon for appropriate construction of disciplinary knowledge that may then enable them to solve a particular problem or task. In this regard, the term *disciplinary affordance* was introduced (Fredlund, Airey, & Linder, 2012)—the use of this term is discussed in Section 3.4.4.

3.4.1. Critical constellations

Physics today mainly deals with physical phenomena that cannot be perceived by the sensory modes—e.g. X-rays, magnetic fields, solar neutrino showers, etc. Hence, gaining access to the physics concepts, laws and theories that encapsulate knowledge of phenomena can no longer be accomplished by simple observation, rather students gain access to physics concepts by engaging with the semiotic resource systems which the disciplinary community has decided best represent those concepts. The process of refining and updating these 'gateway' systems of meaning-making follows more or less the same trajectory as the updating of the knowledge itself. In physics, this often occurs over long periods of time, with each step embedding knowledge a little deeper from the perspective of the novice learner. Furthermore, each individual resource system typically only gives access to one or two aspects of any given physics concept.

Physics concepts therefore typically require a whole set of semiotic resources from a range of systems in order to construct holistic understandings. Therefore, in order to construct an understanding of a concept, a set of semiotic resources need to be *coordinated in combination*; for example, an equation with a graph. And to gain full disciplinary access to a concept requires the deployment of a *critical constellation of semiotic resources:*

A critical constellation of disciplinary semiotic resources with a finite set of pre-assigned disciplinary meaning-making potentials is needed for a given task or situation in order to make possible appropriate experience of disciplinary knowledge (after Airey, 2009).

This idea is diagrammatically represented in Figure 3.1. Mathematical resources give access to three of the critical aspects of the hypothetical physics concept, experimental work gives access to two additional but different aspects. A diagram then gives access to one of each of the aspects the other two systems give access to, and therefore facilitates a meaning-making bridge between the mathematical and experimental systems. The question mark denotes the fact that in the educational community we usually do not know what the full set of resources necessary to achieve a critical constellation is. Students experiencing a critical constellation would entail them being able to appropriately work with each of the individual semiotic resources in the set, and coordinate them in a way that leads to successful task solution. Section 6.1.4 describes the central role that a persistent representation played in facilitating meaning-making with other resources—see also Fredlund et al. (2012).

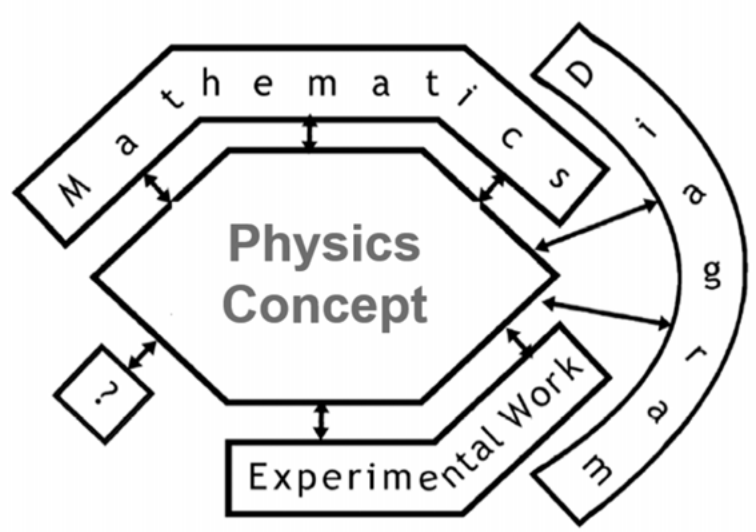


Figure 3.1. Theoretically, full holistic understanding of a physics concept is only possible with a critical constellation of resources (adapted from Airey, 2009).

3.4.2. Fluency

The notion of fluency is central to the UUPER social semiotic framework. The linguistic metaphor is used to signal mastery of a particular semiotic system. Some PER scholars have talked about this concept in terms of students developing representational competence (Kohl & Finkelstein, 2005). Fluency is defined as follows:

Fluency in working with a disciplinary resource is achieved by one coming to understand the particular way(s) that the discipline uses that resource to share and work with physics knowledge in a given context and situation (Airey & Linder, 2017, p. 102).

As they go on to suggest (see Airey & Linder, 2017, p. 103), students cannot achieve full, holistic understanding of a disciplinary concept until they have at least achieved some level of fluency in each of the resources that make up the critical constellation applicable to that concept. Elsewhere, Airey & Linder

(2009) claim that such fluency can only be achieved after a period of what they call *discourse imitation*[27].

3.4.3. Beyond discourse imitation

One of the main findings of PER studies over the years has been that students are often able to perform physics calculations without the associated understanding of the underlying concepts. This has been shown to occur even at the most prestigious universities with the 'best' students; see the discussion in Section 2.2, Mazur (1992), and diSessa (1993). The Harvard and MIT students Mazur and diSessa were writing about may be said to have achieved fluency in the mathematical resource system—they could after all solve a range of complicated problems at an advanced level—yet they still lacked the associated physics conceptual understandings.

After analysing a set of interviews with upper-division students about their experiences after courses on advanced mathematically-dense physics topics (Maxwell's equations and electromagnetism in the one study, and a course on tensors for advanced-level physics students in the other), Airey (2009) found that students can exhibit fluency in certain semiotic resources with respect to the physics content, but still show signs of discourse imitation (i.e. they still cannot fully grasp the concept). See Sections 6.1.1 and 6.1.6 for discussions of how this term was leveraged in Paper III, as well as 6.4.5 for Paper V.

It is therefore argued that fluency in a range of disciplinary-specific semiotic resources is a necessary—though not sufficient—precursor to appropriate constitution of disciplinary knowledge. What is finally needed for students to achieve a holistic understanding is an *appreciation of the disciplinary affordances* of a critical constellation of semiotic resources (Airey & Linder, 2015).

3.4.4. Disciplinary and pedagogical affordance

The term *disciplinary affordance* was coined by Fredlund et al. (2012) to characterise the particular meanings that have been assigned to a given resource by a discipline. Further refinement of the concept led to the following definition:

Disciplinary affordance is the agreed meaning-making functions that a semiotic resource (system) fulfils for the disciplinary community (Airey, 2015, unpaginated).

[27] Discourse imitation is the ability to use discipline-specific semiotic resources with limited or no associated disciplinary understanding. For example, a student may be able to perform calculations with a set of equations, without grasping what the resources mean for the physics.

In a discipline such as physics, learning can be characterised then in terms of coming to appreciate the disciplinary affordances of the semiotic resources employed in the discipline (Airey, Eriksson, Fredlund, & Linder, 2014). Wu & Puntambekar (2012) introduced the term *pedagogical affordance* to the describe the role of certain non-disciplinary representations in teaching science. Building on this work, Airey (2015) defined pedagogical affordance as follows:

Pedagogical affordance is the aptness of a semiotic resource for the teaching and learning of some particular educational content (Airey, 2015, unpaginated).

Where disciplinary affordance deals with the meaning-making functions assigned to a given resource by the discipline (in this case physics), pedagogical affordance deals with the usefulness of the resource for learning the discipline. Thus, whilst the disciplinary affordance of a resource is fairly non-negotiable, the pedagogical affordance of the resource has a student-dependent aspect. In a recent article, Airey & Eriksson (2019) theorise about the relationship between pedagogical and disciplinary affordances of semiotic resources and postulate four types of resource depending on the relative levels of pedagogical and disciplinary affordance. This is depicted diagrammatically in Figure 3.2.

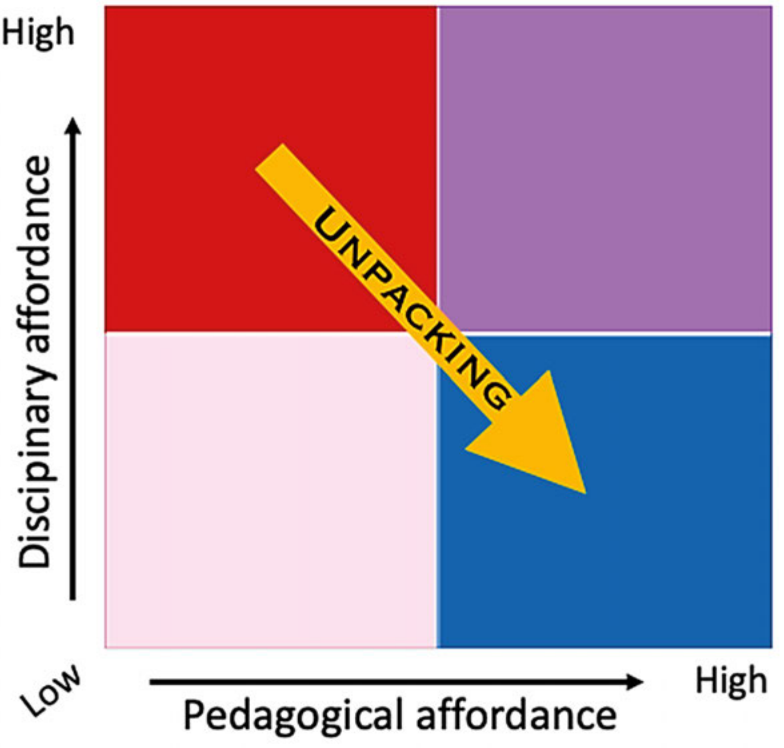


Figure 3.2. Disciplinary and pedagogical affordance. A resource with high disciplinary affordance, but low pedagogical affordance, can be unpacked for students. This increases the accessibility for students, but necessarily lowers the disciplinary affordance—i.e. the utility of the resource to 'do' the discipline (Airey & Eriksson, 2019, p. 101).

The pink area (bottom-left) in Figure 3.2 represents resources with low pedagogical affordance and low disciplinary affordance—we can therefore ignore this area since there is no motivation to use such resources in the teaching and learning of physics. It is the other three fields that are of interest. First, the purple field represents resources with high disciplinary affordance and high pedagogical affordance. We might characterise such resources as the physics lecturer's dream—resources that are both useful for doing physics and teaching physics. Such resources are unproblematic and are therefore seldom in focus for PER. More interesting (and typical) are the disciplinary resources within the red field. These resources are very good for doing physics, but poor for explaining physics—often due to their abstract nature. Working with a circuit diagram, Fredlund, Linder, Airey, & Linder (2014) were the first to suggest *unpacking* of such resources for students. In Figure 3.2 we can see that whilst unpacking raises the pedagogical affordance of the resource the process also lowers the disciplinary affordance making the resource less useful for doing physics. Students will therefore need to 'reassemble' the original resource in order to function efficiently within the discipline. See Sections 6.1.1, 6.1.2 and 6.1.3 as to how these terms were leveraged to characterise the meaning-making potentials of physics devices in physics and within the teaching and learning of physics (Paper III) and V.

3.4.5. Disciplinary relevant aspects: the variation theory of learning

The *Variation Theory of Learning* (VTL) suggests simply that humans notice things that change—for a general view of VTL and some applications in physics, science and mathematics education, see Ingerman, Linder, & Marshall (2009); Marton (2006); Marton & Trigwell (2000), and Runesson (2005). This fact can be leveraged by teachers to help their students notice salient disciplinary features by varying them against an unchanging background. These 'disciplinary relevant aspects' are what we expect students to notice when we teach (Fredlund, Airey, & Linder, 2015). Physics concepts display a wide range of disciplinary relevant aspects, but typically only a few of these need to be leveraged for any given task. Airey & Linder (2017) demonstrate theoretically how such disciplinary relevant aspects can be made available to students through selection of appropriate semiotic resources. A useful schematic of the process of choosing an appropriate set of semiotic resources is given in Figure 3.3.

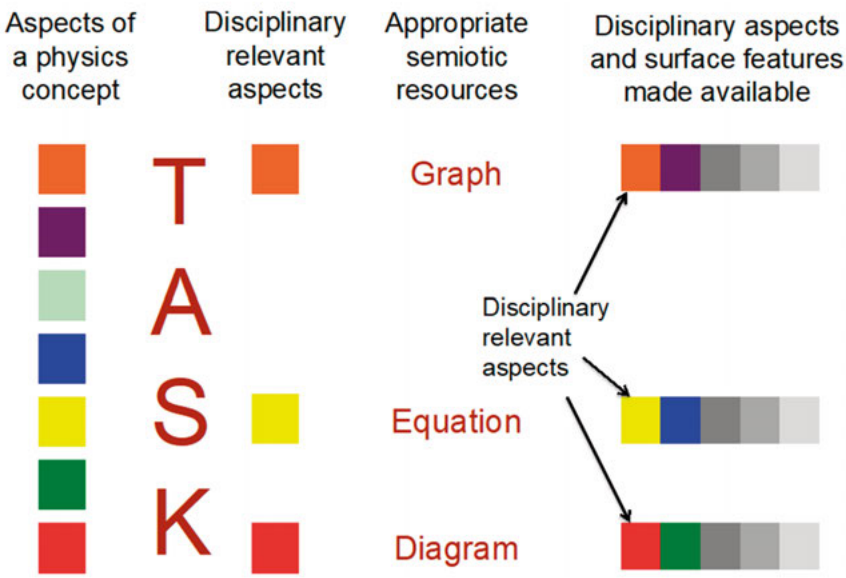


Figure 3.3. Appropriate selection of semiotic resources. For the task analysed, three semiotic resources (a graph, an equation, and a diagram) each allow access to one of three aspects of a physics concept. Notice that each of the selected semiotic resources possesses affordances that potentially give access to other aspects of the physics concept, in addition to some surface features. It is through variation that teachers can then make these aspects noticeable for their students (Airey & Linder, 2017, p. 116).

In this figure, a particular physics concept has a range of different aspects, denoted by the seven different colours. However, for the task at hand, students only need to access three of these aspects – the orange, yellow and red ones. Knowing this, a teacher chooses semiotic resources that best make these aspects noticeable; in this example a graph, an equation and a diagram. These semiotic resources make noticeable other aspects of the disciplinary concept that are not needed, along with a range of surface features (the grey boxes) that are irrelevant for the physics discipline. Teachers direct their students' attention away from these other features and towards the intended disciplinary relevant aspects by using variation (Marton, 2015; Marton & Booth, 1997; Pang & Marton, 2013).

Section 6.2.2 ('The role of variation – leveraging an invisible phenomenon to learn about an abstract mathematical tool') shows how the VTL was utilised though operation of a probeware tool, the iOLab, to make visible for students a key disciplinary affordance of an abstract mathemtical tool, the movability of a Cartesian coordinate system.

3.4.6. Transduction and transformation – a new direction for PER representational work?

This chapter so far has laid out the salient parts of the social semiotic framework developed by UUPER over the last fifteen years. It has also provided the theoretical underpinnings of the conceptual framework used for this thesis. In this section I set out a question I was tasked with answering, when I joined the group in 2016.

Within the field of multimodality, scholars had been using a pair of terms *transformation* and *transduction*, to make a subtle but for them important distinction between the ways that meanings can be shifted between representations. Transformation is used to describe the shifting of meaning between resources *within the same resource system*, whilst transduction is used to describe the shifting of meaning between resources *across different semiotic systems* (Bezemer & Kress, 2008, p. 169).

I began my PhD work by planning to explore the social semiotic distinction between transformation and transduction. The question was whether this distinction that is used outside PER could have useful consequences for the development of the UUPER theoretical framework? I was tasked to investigate the definitions of these terms, as offered by Bezemer & Kress (2008), for application and relevance for physics multi-representational work and to assess whether these multimodal concepts could have traction within the UUPER theoretical framework. However, I quickly came to the realisation that transduction was the most relevant and important aspect to explore. This is because my first data set showed that transductions were, in fact, inherently more powerful in learning situations than transformations. Furthermore, transductions had not been the focus of any published work in PER at that stage and it seemed a distinct weakness that this aspect had been overlooked for research dealing with student learning in physics. From that point onwards, the central focus of my thesis became investigating the role of transduction in physics in general and its importance for the teaching and learning of physics in particular. Coming full circle, in studying the role of transduction in students' learning about a semiotic system in which transformations are also involved, this thesis will suggest avenues for future work to study the relationship between transformation and transduction in physics teaching and learning.

Section 6.1 discusses the role of transduction in physics, both in the meaning-making practices of the discipline, and in the teaching and learning of physics. In particular, Section 6.1.3 applies my conceptual framework to characterise the iOLab as a transduction device with high disciplinary and pedagogical affordances. Further sections similarly leverage other constructs and concepts discussed in this chapter.

3.5. Multimodal social semiotics

This study sought to investigate how learning takes place in a given situation that involves continuous shifts between semiotic resources, and in particular the transduction between these resources. To this end, multimodal social semiotics was therefore selected as the basis for the analytical approach adopted for the thesis work—see also Sections 4.3 and 4.4.

Goodwin (1979) and his colleagues at the time were able to demonstrate the value of gathering evidence from a variety of non-textual sources in order to study the shifts in meaning that occur in diverse discourse types (for example, the use of video recordings to study gaze). The field of multimodality (see Jewitt et al., 2016) emerged from Goodwin's work and that of other researchers, most notably (Hodge & Kress, 1997), and Kress & Van Leeuwen (2006). From the perspective of this group of researchers, individual semiotic resources used in a discourse are seen as 'incomplete', i.e. meanings are in constant flux and at any one-point new meanings may be negotiated. In other words, meaning is always in the process of being made anew. In contrast, in physics there are agreed meaning-making potentials (disciplinary affordances) attached to physics-specific semiotic resource systems. For example, for many physicists a single mathematical equation can be seen as sufficient to describe a particular phenomenon. Naturally, physics practitioners must also be able to make the necessary semiotic shifts when resources are called upon in different contexts, and appreciate their disciplinary affordances for giving access to concepts up and down the hierarchical levels of physics knowledge.

4. Methodology

I see methodology as being about a method and the theory that guides that method. For this thesis, a significant aspect of that theory is introduced in Chapter 3 in terms of the conceptual framework that underpins the entire thesis. The other theoretical aspects that facilitate appreciation of the appropriateness of the method used to answer my research questions are given in Chapter 5. The methodological depiction that relates to the broader categorisation of my method—qualitative case studies—are given attention in this chapter. I decided to use this distribution of methodological discussion because I saw it as necessary to build coherence into my thesis construction.

The first section of this chapter briefly introduces *qualitative research* as an appropriate analytic approach to answer the kind of case study research questions posed for this thesis. The next section discusses *case study* aspects and goes on to address the issue of rigour and quality: the concept of *trustworthiness* and what kind of *generalisation* could be possible for my studies.

The final three sections of the chapter return to details of my study as a way of preparation for what follows in the next chapter (5) that describes the method(s) I used for my work.

4.1. Seeking understanding: qualitative research in PER

Using a qualitative research approach in PER is not uncommon. At the time of writing, a search in the flagship journal for PER, Physical Review—Physics Education Research, using the keyword "qualitative study", found 270 articles. It is also not new. For many years now, the research approaches used in PER have spanned a wide range of research methodologies; both qualitative and quantitative case studies and large-scale quantitative statistical studies. The need for qualitative studies that seek to better understand physics learning situations is presented as follows by Otero and Harlow in their PER Review contribution entitled *Getting Started in Qualitative Physics Education Research*:

> Many studies in PER have produced convincing quantitative results that have informed our understanding of how students learn physics. For example, PER studies have demonstrated higher learning gains in courses that use methods of interactive engagement than in courses that use traditional lecture methods,

> identified gender differences in students' scores on standard assessments, and shown differences in students' expectations for learning physics and that these views decline over a single semester. While these types of studies are very useful and provide much information about teaching and learning physics, researchers often want more detail that can help them better understand these types of replicable trends. This is why many PER researchers decide to engage in qualitative research studies. Qualitative research studies use different types of data and analysis methods than quantitative studies, but like quantitative studies, they use evidence to make and support claims about physics learning and teaching.
>
> (Otero & Harlow, 2009, p. 2)

The first three chapters of this thesis make a case for studying the fine-grained aspects of students learning about physics concepts in laboratory tasks; where active learning is encouraged through engaging students interactively with each other, facilitators, and a range of semiotic resources. The task design around a probeware tool (the iOLab), which encouraged and facilitated interactive engagement, was another supporting motivation for studying how students use, construct and communicate meanings within these types of learning settings. This meant that the speech and actions of students and facilitators needed to be recorded, transcribed and interpreted. As such, my analysis followed a qualitative approach seeking understanding, i.e., an interpretative research approach—see the discussion by von Wright (1971, p. 6).

4.2. Case study research

Since all my work involved case studies—although they are a well-established research approach in PER—I am including a short introductory discussion on case studies.

The research questions of this thesis involve both descriptive ('what') and explanatory ('how' and 'why') threads aimed at generating understanding rather than traditional confidence in predictions in terms of generalisation. To answer these questions, case studies are useful (see Yin, 2006, p. 112). In case study research, the researcher is interested in, "[bringing] out the details from the viewpoint of the participants" (Tellis, 1997, p. 1). Many different ways of conducting case study research have been developed over the years, and in PER there is a wide adoption of qualitative research approaches within a broad spectrum of applications—see the review article about "case-oriented PER" by Robertson, McKagan, & Scherr (2018).

My case studies were undertaken in an educational setting, a context summarised by Bassey (1999) as follows:

> An educational case study is an empirical enquiry that is conducted:
> - within a localized boundary of space and time (i.e., a singularity);

- into interesting aspects of an educational activity, or programme, or institution, or system;
- mainly in its natural context and within an ethic of respect for persons;
- in order to inform the judgments and decisions of practitioners or
- policymakers, or of theoreticians who are working to these ends;
- in such a way that sufficient data are collected for the researcher to be able to:
    1. explore significant features of the case;
    2. create plausible interpretations of what is found;
    3. test for the trustworthiness of these interpretations;
    4. construct a worthwhile argument or story;
    5. relate the argument or story to any relevant research in the literature;
    6. convey convincingly to an audience this argument or story;
    7. and provide an audit trail by which other researchers may validate or challenge the findings, or construct alternative arguments.

(Bassey, 1999, p. 58)

To address the ethical issues associated with ‘conventional’ approaches, Lincoln & Guba (1989) argued for a paradigmatic shift in naturalistic inquiry. In so doing, Lincoln & Guba present an equivalent construct that they called “trustworthiness”. *Trustworthiness* is discussed further in Section 4.2.1.

This thesis is positioned within naturalistic inquiry. When formulating the initial research questions of this PhD study, and the concomitant approaches of data collection which would be most appropriate, a number of critical considerations arose. To understand what was occurring in a moment-to-moment basis, in an authentic learning setting where student activities form part of their usual curriculum, it was decided that the research team involved in this study would immerse themselves inside the learning activity, i.e. be *participant-observers*. I have described them as ‘facilitators’.

Participant-observation brings with it its own challenges (see Yin, 2009, pp. 111–113, for a discussion of this approach, and its associated issues). Personal bias is the principal problem—for the researcher is less able to be an ‘external’ observer; is likely to ‘advocate’ within the particular social setting (see also the discussion in Stake, 1995, p. 93). Thus, as the activity unfolds, the researcher may not be able to gain an alternative perspective, which is deemed important for observational studies.

In each of the case studies reported on in this thesis, the video recordings of the students’ engagements with one another, the probeware device and with their facilitators, were the main form of data collected. Further observational data was gathered by the principal investigator (the author of this thesis) during the laboratory sessions.

4.2.1. Rigour: trustworthiness in case study research

The rigour of conventional research work in the natural sciences is often predicated on the extent to which internal validity, generalisability, reliability, and objectivity are met. In response to these four criteria, Lincoln & Guba (1989) developed their parallel or foundational criteria—what they have collectively termed trustworthiness—and in so doing, introduced the respective parallel terms *credibility*, *transferability*, *dependability*, and *confirmability*, for naturalistic inquiry. I now deal with each of these in turn.

Credibility, which parallels internal validity, sees the researcher striving to establish the truthfulness of one's data and the integrity of the research process as a whole. Peers and colleagues, approved within the ethical guidelines followed—see Section 5.4—, were consulted to view the video data and inspect the transcriptions—see Section 4.3. The data analysis process allowed for an iterative refinement of the transcripts—the production of the transcripts was therefore a result of analysis, as well as the data corpus to analyse the multimodal sequences to answer the research questions. In this way, credibility was established.

Transferability parallels generalisability. The kind of generalisation that I anticipate being available from my studies is what Stake (1978) referred to as a "natural basis for generalization" based upon experience. In other words, for a potential user of my results, my descriptions facilitate recognition from experience—a "naturalistic generalization":

> What becomes useful understanding is a full and thorough knowledge of the particular, recognizing it also in new and foreign contexts.
>
> That knowledge is a form of generalization too, not scientific induction but naturalistic generalization, arrived at by recognizing the similarities of objects and issues in and out of context and by sensing the natural covariations of happenings. To generalize this way is to be both intuitive and empirical, and not idiotic.
>
> Naturalistic generalizations develop within a person as a product of experience. They derive from the tacit knowledge of how things are, why they are, how people feel about them, and how these things are likely to be later or in other places with which this person is familiar. They seldom take the form of predictions but lead regularly to expectation.
>
> (Stake, 1978, p. 6)

Drawing on the work of Geertz (1973), Stake & Trumbull (1982) later go on to argue that a sufficiently 'thick', situated description of the research should be able to satisfy the transferability yardstick of trustworthiness. The thick descriptions provided regarding the methods (Chapter 5) and analysis (Chapter 6) is intended to provide the reader with enough information to both judge the work and evoke naturalistic generalisability. Here it is important to also point out that trustworthiness is ultimately dependent on the relationship between the researcher, the data, and the research questions. Judgements about the extent to which an individual case study is trustworthy, can however only be made independently by the individual readers of the studies.

The third foundational criteria proposed by Lincoln & Guba (1989) is *dependability*, which is parallel to the conventional criterion of reliability in that it is concerned with the stability of data over time. It should be noted that the approach used in this thesis, that emphasises “research as process”, acknowledges that questions for study will emerge during the course of the ongoing cycle of data-collection and analysis which characterises (and powers) one’s work. As described earlier (see Chapter 1), this was certainly true for my study, where the experiences of the first case study informed the subsequent two case studies.

The fourth criteria, *confirmability*, is parallel to the conventional criterion of objectivity. Confirmability is concerned with assuring the reader that the data and interpretation presented in the thesis are rooted in context and not simply a figment of one’s imagination. Here the assurances of integrity of the findings are rooted in the data themselves—Appendix A provides a full transcript and the following two chapters provide further details.

Before proceeding to the next Chapter, Methods, three things need to be introduced in terms of methodology. First, how systemic-functional multimodal discourse analysis (SF-MDA) influences my approach to multimodal transcription. Second, is seeing multimodal transcription as transduction. And third, using video as data.

4.3. Theory of meaning: the role of SF-MDA and Social Semiotics

The theory of meaning that I drew on for my thesis work was derived from Jewitt et al.'s (2016) characterisation of the aims and theory of meaning of Systemic Functional-Multimodal Discourse Analysis (SF-MDA) as it applies to multimodal approaches:

> Meaning systems are conceptualized social semiotic resources for creating meaning. The meaning potential of a system is reflected in its underlying organization that is modelled as interrelated systems of meaning. The systems are ‘networks of interlocking options’ (i.e. choice between different forms), and ‘text’ is a process and product of the selection (and materialization) from that potential.
>
> (Jewitt et al., 2016, p. 131)

So, although I would not claim that I carried out SF-MDA, the theory of meaning that I anchored my thinking in fits that of SF-MDA as per the above description. This approach does allow for a consideration of the re-semiotisation across resources which may result in additional meanings being accessible beyond those available when only using the resources individually. This is similar to the claim of Airey (2012, p. 73) who draws on Lemke, 1998a) to suggest that a combination of semiotic resources may lead to emergent meanings that are more than the sum of those obtained from the individual resources

Because of the conceptual framework underpinning my work, this thesis adopts a disciplinary discourse view of physics, and given the epistemology of the discipline of physics, a brief look at how students' work with analysing representations from a multimodal perspective has been reported upon in the literature, provides further background on the methodological approaches taken in this thesis.

Tang, Delgado, & Moje (2014) performed a type of multimodal analysis which focused on the modal connections between representations. They used a framework that studied the textual representations (i.e. diagrams with text) students used and the links between the different representations. They analysed thematic diagrams at the textual level by utilising a theory of meaning, similar to that used by SF-MDA. In a relatively recent study, O'Halloran (2015) employed an SF-MDA approach to explore how the integration of specialised language, images and mathematical symbols gives rise to new views of the physical world, that are not possible through language alone, or through any of the other individual semiotic resources.

4.4. Multimodal transcription as transduction

This section explains how the multimodal nature of the students' interactions and engagements with the set of available resources were documented and preserved in the transcripts. It is worth noting, that within the broad field of multimodality, the act of transcription itself may be viewed as a transduction (Flewitt, Hampel, Hauck, & Lancaster, 2014, p. 52). This is because video data is recast into a new 'mode', that is text. The knowledge of the transcriber and skill in representing accurately what was said and done, for the purposes of answering the research questions, is paramount. Because this transduction depends on the transcriber, additional trustworthiness checks need to be implemented—see Section 4.2.1.

The spatial and temporal aspects of the students' multimodal interactions during the laboratory sessions are documented, were preserved in the final versions of the multimodal transcripts included (see Appendices A and B for the two different approaches that were adopted for capturing and analysing the data collected from the three cases studies). For Case Studies (A) and (B), the transcripts were comprised of speech and action converted into text (see Appendix A) while for Case Study (C), photographs and superimposed gesture arrows were also included (see Appendix B). Both approaches were deemed to be equivalent for the purposes of answering the research questions.

In the transcript accompanying Case Study (C), after assessing the value of adding in the pictures, it was surmised that the addition of photographs required more effort—from the perspective of an uninitiated reader—to understand the multimodal learning that was occurring, and did not add anything new to the descriptions. The work on refining the multimodal transcription that was effective in communicating the richness of the resource usage observed, was heavily influenced by Bezemer & Mavers (2011).

4.5. Using video data

The analytical approach adopted in the three case studies commenced with the identification of important learning sequences or events, followed by the seeking out of patterns in the data. This was undertaken in iterative cycles which involved reviewing the video data, and scrutinizing the evermore-refined transcripts (see Section 5.3.1). The goal of such analysis is to distil out either a rich description or a trustworthy explanation of the data—see Bogdan & Biklen (1992, p. 153). As discussed before, this is how transferability or generalisability is established in case study research.

From the early years of PER, where audiotapes were first used to record interviews with students, to today, where digital video recordings of students engaged in a range of physics learning activities have become commonplace; the interest of researchers has been to extend analysis of student work beyond a consideration of their answers to concept-based questionnaires or problem-solving products, such as answers to tutorial or examination questions. In an attempt then to develop a more nuanced understanding of the complexities of the learning process, students' speech, actions, engagements with tools and equipment, and gestures, have become incorporated into the analysis—as exemplified by the multimodal analysis of this thesis.

The synchronicity of talk, actions and gestures were of specific interest in my research. Gestures in particular are currently being studied across a wide range of disciplines, and their significance for different research communities has proved to be as diverse as the range of interests. For example, in the emerging field of multimodality, gesture is viewed as yet another mode which accompanies speech or text and possesses certain meaning-making functions for a particular setting or use (Bezemer & Kress, 2008). Closer to our field (PER), Scherr (2008) provides a useful review of research into gesture analysis which provides a tool for "better understanding [of] student thinking" (Scherr, 2008, p. 1). Other notable work includes that of Goodwin (2003), who used video data to explore the specific disciplinarily-unique gestures used by archaeologists during field work activities. Even though the research in this thesis does not draw explicitly on cognitive perspectives such as embodied cognition, the study of gestures by researchers from a wide range of fields does demonstrate their importance in analysing how students may be making sense of and conceptualising disciplinary knowledge.

This thesis focusses on the students' moment-by-moment usage of the semiotic and disciplinary resources available to them as they engage with each other, the facilitators, and with the probeware device. In order to capture the talk and actions of the students and the facilitators, both video and audio recordings were made of the laboratory sessions.

For the analysis, attention is paid to the coordination of the resources made available to students and the resources they actually use, including bodily gestures, speech, gaze, and introduction of their own resources, for example, drawing their own diagrams.

In his PhD thesis, Fredlund (2015) generated multimodal transcripts from video and audio data of students working in typical undergraduate physics laboratory settings. He employed a social semiotic lens to analyse the range of resources utilised by the students and was able to identify thematic patterns. Fredlund was able to identify the key disciplinary relevant aspects which the students had to access in order to ensure that effective meaning-making would take place in tasks involving multiple representations and showed the critical role of a persistent representation around which other non-persistent resources could be coordinated—a coordinating hub. Although not discussed in Chapter 3, the notion of coordinating hubs is a key theoretical construct used in this thesis and will be discussed in more detail in Chapter 6, in particular Section 6.1, and again in Section 6.4.

5. Methods

This chapter presents the case studies and the methods that were employed to collect and analyse the data. The three student cohorts and their contexts, followed by the two learning tasks are first described. Thereafter, the laboratory setups and the methods used to collect the video data of the students' engagement with the tasks and the semiotic resources made available to them are presented. Finally, the method of data analysis (multimodal transcription) that produced the research findings, as well as the implementation of ethics guidelines, are described.

5.1. Case studies

5.1.1. Case Study (A) – (Papers I, II, III)

Case Study (A) involved 22 students at a Swedish upper secondary school (gymnasiet). The rationale for selecting this group of students, who were in the final weeks of their penultimate year of schooling, is explained in Section 5.1.2. All the students who agreed to participate were between 17-19 years of age at the time of the data collection and, although their classes were taught in Swedish, were comfortable using English for their discussions.

The study itself involved students working in pairs on an 'open-ended'[28] task in a student laboratory setting that involved using the iOLab probeware tool (for more details on the iOLab, see Section 5.2). The laboratory tasks were designed with two purposes in mind. Firstly, to provide students with experiences that would enrich their learning of basic, yet difficult to grasp, disciplinary aspects of physics concepts—this included a key disciplinary affordance of an abstract mathematical tool (coordinate systems); and secondly, to meet my research goals of providing multimodal data about how students interactively learn new things in laboratory settings. For a discussion on the challenges that students experience with learning about coordinate systems, see Section 6.2.1.

[28] I use the term open-ended loosely here to signify that the task did not have a preset procedure, was exploratory in nature from the students' perspective (the facilitators did have a good idea of the optimal path to solution), and the facilitators took their cues from the students in the Socratic dialogues which occurred.

To this end, students used the iOLab probeware tool to determine the direction of the Earth's magnetic field, an invisible phenomenon, whilst working with a mathematical tool, a 3D Cartesian coordinate system, that the students, up until then, had largely experienced in abstract and esoteric terms.

With the cooperation of the students' physics teacher, the activity was scheduled to coincide with the timing of the topic in the curriculum—the students had just been introduced to a 2D Cartesian coordinate systems a week before the planned activity. Data were collected on two separate laboratory sessions, each of approximately 80 minutes' duration, and involved six and five pairs of students respectively. The engagement of one pair of students was then purposefully selected (Suri, 2011) for further analysis.

5.1.2. Case Study (B) – (Paper IV)

Case Study (B) was undertaken at a South African university and involved students who were registered for a two-year (extended curriculum) introductory physics course. The 14 students who participated in the study were between 17-19 years of age at the time of data collection. They too were comfortable using English in their discussions[29].

Seeing as Case Study (A) was originally intended to be a pilot study to Case Study (B), the gymnasiet students were deemed to be equivalent to their counterparts in South Africa in terms of age and prior physics knowledge. Apart from a number of understandable differences, such as the personal backgrounds and languages of the students' in the two countries and the use of local teachers/lecturers to facilitate the laboratory activities, the setting of Case Study (B) was identical in all respects to that of Case Study (A). The fact that the Earth's magnetic field points *out of* the ground in South Africa, as opposed to *into* the ground in Sweden, was seen as an interesting added dimension to the study.

Selection of, and access to, the 14 students was arranged with their physics lecturer. Due to physical constraints, only three pairs of students could participate in each laboratory session; resulting in two groups with three student pairs, and one single pair in the third session.

5.1.3. Case Study (C) – (Paper V)

Six, first-year trainee physics teachers at a Swedish university participated in this study. These students were enrolled in a first year introductory course for pre-service physics teachers which is designed to expose them to a selection of topics (both in physics and education) deemed relevant for teaching physics

[29] Although English was the medium of instruction at the South African university the case study was conducted, this mixed language group of students had home languages ranging from English to Afrikaans and other indigenous South African languages.

at upper-secondary level in Sweden. As in Case Study (A), the participating students communicated in English.

Working in pairs, the students engaged in an activity designed for them to practice and develop representational competence in 1-D kinematics (see Section 6.4), in particular motion graphs (position-time, velocity-time, and acceleration-time). They did so using the same probeware tool, the iOLab, that was used in Case Studies (A) and (B).

Whereas the number of students involved in the study was quite small, experience gained in the application of the social semiotic lens in Case Studies (A) and (B) had shown that sufficient data could be obtained from the analysis in terms of what is characterised as "learning sequences". The aim was to collect in-depth descriptions of the students' interactions with each other and their use of the available semiotic resource systems for later analysis. See Paper V and Section 6.4.4).

5.2. The iOLab and the learning tasks

The case studies for this thesis were designed around the use of a probeware tool, the iOLab, in authentic laboratory tasks, which typical introductory physics students may encounter in their courses. Ultimately, the open-ended laboratory tasks were designed around the interests of tertiary physics educators wanting to provide their students with better learning experiences in the laboratory, i.e. create better possibilities for them to grasp physics concepts, as well as that of the research goals of providing data about how students make meanings in laboratory settings using laboratory tools. Section 6.1.2 presents the semiotic analysis I made of the functions of the iOLab revealing its usefulness for both doing physics *and* teaching physics.

The learning goals for the tasks were driven by dual interests—educational and research—in enriching student learning of basic, yet difficult-to-grasp, disciplinary aspects of physics concepts. Chapter 6 provides a synthesised discussion around these aspects and the findings of the three case studies, produced by applying the conceptual framework discussed in Chapter 3.

The iOLab— "*an interactive Online Laboratory system*"—is a laboratory system designed to be used in physics teaching and learning (see Figure 5.1). Using its array of on-board sensors (3D magnetometer, 3D gyroscope, 3D accelerometer, optical wheel sensor, force probe, microphone, light intensity sensor, atmospheric pressure sensor, temperature sensor, connections to do electric circuit experiments) a host of physical phenomena can be investigated—see (Ansell, 2020; Selen, 2013)[30] for a representative set of examples

[30] The webpage www.iolab.science includes links to the resources produced by the PER team at the University of Illinois at Urbana-Champaign.

of possible activities and experiments. This educational tool has recently attracted the attention of developers of physics courses, most notably in active learning laboratory courses (Bodegom, Jensen, & Sokoloff, 2019; Holmes & Wieman, 2018; Nair & Sawtelle, 2018; Sokoloff, Bodegom, & Jensen, 2018). Since the device has generic pedagogical and disciplinary affordances, these need to be leveraged for teaching through the creation of a concrete learning task.

Figure 5.1. The iOLab system. The device enclosure (sensor-box) connects wirelessly via a transmitter-receiver (USB dongle) to a computer. Its mass is ~200 g with dimensions 13×7.5×3.0 cm. The required sensor is selected from a drop-down menu to the left of the interface screen. Real-time data is then displayed in graphs to the left. (Paper II, p. 7)

5.2.1. Case Studies (A) and (B): the iOLab and the 3D magnetometer sensor

The iOLab's 3D-magnetometer sensor measures the strength of the magnetic field in three mutually perpendicular directions which are independently plotted on a graph in real-time. Note also the printed set of axes on the iOLab device enclosure (Figures 5.1 and 5.2); henceforth simply referred to as the sensor-box. This turned out to be one of the more important features of the iOLab system, for our task and intended learning goals. It allows students to connect the displayed graphs (each component in its own colour) to physical directions in space via visual cues. Furthermore, the sensor-box, with its small dimensions and weight (see the caption of Figure 5.1), can be hand-held and easily manipulated. Students can use their proprioception (the sense of how their body is positioned in space) to 'feel' the orientation of the sensor-box as they move it, while they pay attention to changes on the computer screen. In this way, they can attend to the graphs on the screen and the spatial orientation of the sensor-box simultaneously, using separate modes of perception.

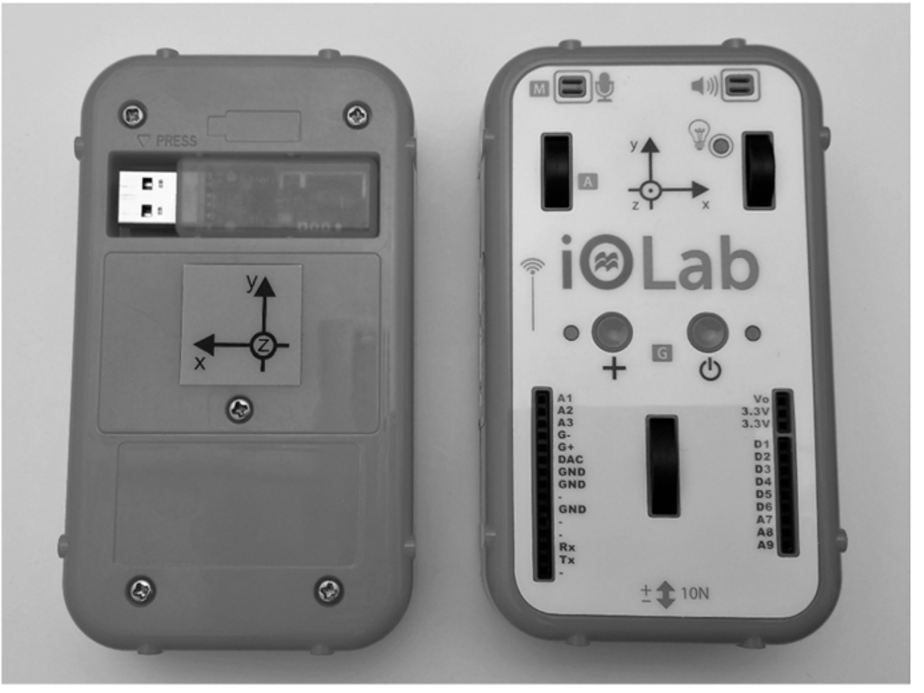


Figure 5.2. The iOLab sensor-box. This photograph shows the top and bottom faces of the sensor-box. The USB stick serves as the wireless transmitter-receiver connecting the computer and the sensor-box.

The task for Case Studies (A) and (B) was designed around students investigating a phenomenon that they cannot directly sense; the Earth's magnetic field. This was intentional; since most physics phenomena under study today are not accessible through the sensory modes, students have to learn how the disciplinary community have decided to represent the important features of the phenomena the discipline dictates. Chapter 6 includes a theoretical discussion developed during the course of this thesis about the role and functions of physics devices from a social semiotic perspective—Sections 6.1.1–6.1.3.

The iOLab system then, through providing a real-time display of the three Cartesian components of the magnetic field on a computer monitor, provides a means by which students can 'experience' the magnetic field. The set of axes printed on the top and bottom faces of the sensor box show the orientation of the instrument relative to the reference axes used by the readout system.

In summary, this task revolved around, (i) an interest in developing students' conceptual understanding of an invisible phenomena, the Earth's magnetic field, (ii) exposing students in a more direct way to the use of an abstract mathematical tool (3D Cartesian coordinate system), and (iii) linking students' real-world experiences (manipulation of a sensor-box), facilitated by the iOLab and other semiotic resources, to the chosen relevant aspects of physics-specific concepts (see Sections 6.1 – 6.3).

The classroom-laboratory setup for Case Studies (A) and (B)

In Case Study (A), in preparation for the task, the school teacher ensured that before the lesson the iOLab software was downloaded and installed on the students' laptop computers.

The classroom setup in Case Study (A) is depicted in Figure 5.3. The line sketch is taken from an actual video snapshot. The video camera was positioned in such a way that the computer screen, both students, and the majority of their manipulations and movements could be recorded. A desktop microphone was used to record the students' verbal interactions. This arrangement was used to record each pair of students in Case Studies (A) and (B), a total of three cameras were thus deployed in each session.

Figure 5.3. A student pair from case study A working with the iOLab system. Notice in the background the original placement of the iOLab sensor-box on top of large plastic boxes to isolate the magnetometer sensors from any electric and ferromagnetic sources in the room. (Paper III, p.21)

Three members of UUPER participated as facilitators in the activities for Case Study (A) (see Section 4.2 for a discussion on the methodological reasons for taking this approach to collecting qualitative data). During the course of their involvement, the researchers performed the role of 'laboratory assistant' or 'facilitator', with the students' physics teacher also being a facilitator. Prior to the commencement of the laboratory activities, a meeting was held between the researchers and the teacher to ensure a coherent approach to the interpretation of the task goals.

In Case Study (B), where there were never more than six students participating in each session, only one trained facilitator (the author of this thesis) was used. A computer laboratory assistant, working in the department where the data collection took place, provided laptops for the sessions and software support. In addition, a student unknown to the cohort was employed for additional assistance (camera setup, data downloading, etc.).

In both case studies the students were introduced to the task by one of the members of the research team, speaking in English.

The richness of the data which emerged in Case Study (A), in terms of student engagement with the iOLab and the other resources, and the subsequent analysis that followed, caused a rethink of the overall design of the study. This resulted in Case Study (B) being re-purposed to follow-on from Case Study (A). In other words, Case Study (A), having started in its role as a pilot study, now became the baseline study for the entire thesis. The data collected and analysed for Case Study (B) was therefore treated as additional information to answer some of the same research questions under investigation in Case Study (A). In a sense then, Case Study (A) could be seen as the *first* stage of a three-part case study design where direct comparisons or contrasts are sought after (see Section 4.2.1).

The task instructions

The students were asked to use the iOLab to find the direction of the Earth's magnetic field and mark its direction using a cut-out paper arrow. Each student pair was also provided with a brief instruction sheet in Swedish (half an A4 page, see Appendix D for the English translation). No other information was provided. Students worked in pairs, with their interaction recorded by a fixed video camera and desktop microphone (see Figure 5.3 for a line sketch of a snapshot of an actual classroom scene).

5.2.2. Case Study (C): the iOLab and the wheel sensor

The first two case studies confirmed that the iOLab device, with its range of pedagogical and disciplinary affordances, had the potential to be a particularly useful tool for exploring student meaning-making in laboratory work. In Case Study (C), the focus shifted to 1D-kinematics—a well-documented problem area for students (see Sections 6.3.4, 'Graphs in 1-D kinematics – a social semiotic analysis', and the section dealing with 1D-kinematics graphs in Paper V, p. 92). With the three wheels built into the top face of the sensor-box, the sensor-box can also be used as a kinematics cart. The central wheel is monitored by a sensor that tracks the rotation of the wheel. When turned face down, and rolled on a flat surface the box moves in or opposite to the *y*-direction printed on its face (see Figure 5.2). Graphs of motion (position-time, velocity-time, and acceleration-time) can then be plotted in real-time on the computer screen. This allows students to connect their visual observations of the motion of the sensor-box to a graphical depiction of this motion.

The classroom-laboratory setup for Case Study (C)

As in the other two case studies, video-recordings were made of the students' interactions with the iOLab device, with each other, and with the facilitators. Given the nature of the task, which involved students moving around the room as the iOLab sensor-box was rolled across the floor or table tops, the fixed video camera and microphone recordings employed in the first two case studies were supplemented with recordings made using two GoPro™ cameras.

For Case Study (C), the facilitators engaged with the students as they worked their way through the three sub-tasks; they were asked to describe and explain what they had just done.

The task instructions

As in Case Studies (A) and (B), the students were not provided with detailed procedural instructions. However, due to the greater complexity of the three sub-tasks (designed to develop representational competence in working with motion graphs in 1D-kinematics), the detail was presented verbally and summarised on a whiteboard. See Sections 6.4.3 and 6.4.4, where a discussion sets out the sub-tasks designed for students to practice the targeted representational competence.

5.3. Method of multimodal transcription

5.3.1. Selection of video sections

How the selection of video sequences for multimodal transcription was made was essentially the same for all three case studies. Thus, a detailed description for Case Study (A) is presented here, before linking this approach to Cases (B) and (C).

The first step in the data analysis involved several members of the UUPER team collectively reviewing potentially interesting aspects of the video recordings of the eleven student pairs. Some of these had been noted down during the activities and, prior to this initial data analysis session, the author of this thesis had reviewed the full video material and noted down the time-stamp of potentially interesting excerpts. The intention of this group viewing was to identify those sequences which best illustrate the rich diversity of multimodal interactions with the iOLab device. Note that given the research setting for case Study A (a Swedish gymnasiet student-laboratory), only discussions which took place in English were analysed. A Swedish speaking member of the research team reviewed the material and confirmed that any exchanges in Swedish generally mirrored those in English. Given the experience of the research team with the types of interactive engagement activities used in this research, after several rounds of member-checking, an agreed understanding of what took place in the selected learning sequences soon emerged. This in turn informed, in an iterative way, the development and refinement of the transcripts.

In Case Study (A), one pair of students was chosen for further analysis and a full multimodal transcription was made of an extended learning sequence lasting approximately 40 minutes (Appendix A). This was due to the rich interactions that occurred in this pair and the fact that these interactions were deemed to be typical of the types of interactions that occurred in the other pairs. For Case Studies (B) and (C) a full multimodal transcription of selected episodes of the interactions of different student pairs was made—an excerpt of such an episode is given in Appendix B.

5.3.2. Transcribing the data

The procedural aspects of my multimodal transcription were informed by the many chapter contributions in the multimodal handbook edited by Jewitt (2017). For the full methodological detail, see Chapter 4. My transcriptions of the selected video sequences provided details of how multiple semiotic resource systems were used and interpreted by students in their quest to complete the laboratory task that they were given. The transcripts also offered a means to capture the moment-to-moment engagements of the students with each other, the iOLab device, and with the facilitators.

By staying true to the flexible qualitative research design of the case studies, the data in the end dictated the style of presentation of the multimodal transcripts—here examples from Bezemer & Mavers (2011) were instrumental in directing the final choice of transcription style.

In order to analyse the function of the modalities of student interaction, my multimodal approach followed approaches described by Baldry & Thibault (2006), and Bezemer & Mavers (2011). This was because one of my central objectives was to capture both the spatial and temporal aspects of the students' multimodal actions as they worked together on the assigned task, and these particular texts provided examples of how this type of transcription may be done. In all three case studies, attention was given to the students' semiotic inter-changes during their manipulation of the sensor-box and their engagement with the resulting graphical depictions of motion (which were displayed on their computer screens). For the data from both Case Studies (A) and (B), particular attention was paid to the students' coordination of the sensor-box's orientation, the three-component graphical readout, and the students' and facilitators' use of speech, gesture and gaze. For Case Study (C), the ways in which the students co-ordinated their observations of the motion of the iOLab sensor-box to the generated graphs and the concepts of motion, was the most valuable data. The students' attention to the printed-on set of axes in all of what I have characterised as "learning sequences" was identified as important; consequently, the students' gaze was an important feature to record in the transcription. The roles each of the semiotic resources played in the meaning making of the students are unpacked in more detail in the next chapter.

The first full multimodal transcription, for Case Study (A), can be found in Appendix A and further discussion can be found in Papers I, II, and III.

5.4. Implementation of ethics guidelines

The procedures necessary for obtaining ethical clearance differed across the three educational institutions involved in the study.

In Case Study (A), access was granted by the lead physics teacher at the school, who arranged a meeting with my research team before, and also participated, in the activity. The offer for teachers to participate in the data collection process was seen as an important factor in ensuring buy-in by the subject teachers whose students would be participating in the study. For Case Study (B), clearance and approval was granted by the university's Human and Social Sciences Research Ethics Committee. For Case Study (C), the university's prescribed research ethics process was followed, which complies with the European Union's General Data Protection Regulation (GDPR), and the Swedish Research Council (2017) guidelines for research involving human subjects.

In all three case studies, consent forms were given to students who had agreed to participate in the study. These forms were signed and returned on the day of the laboratory session. At the start of each session, the students' rights were carefully explained: in particular, that they had the right to withdraw at any time without stating a reason; that no personally identifiable data would be used in any publication or presentation; that all information gathered would be in strict confidence, and that the results of the exercises would in no way form part of any course assessment. Further, since students were to be video-taped, the consent forms also gave students the right to anonymity—they were free to request that no footage showing their faces be used in presentations and publications. Examples of the forms used for the three case studies can be found in Appendix E.

6. Findings

This chapter presents my results. In so doing, it covers two aspects. First, it presents some of the results from my published papers. Second, it presents the results of my thesis research questions. The trajectory of this Chapter takes the reader through a story-line that provides answers to my overall thesis research question (*What might transduction—a theoretical construct common in the field of multimodal social semiotics—contribute to social semiotics research work in PER?*). At the same time my aim is to also bring out the development of theoretical constructs based on the conceptual framework laid out in Chapter 3. The story-line is also intended to bring to light the analysis of the selected student engagements. This is needed as part of the unpacking of the basis for the empirical findings of this thesis that runs across Chapters 1-6. As my conceptual framework evolved, following each of the case studies, it simultaneously informed in a dynamic way the design of the subsequent case studies. In other words, this chapter is not intended to provide a chronological trajectory path of my research work, but rather a path that clearly shows how my theoretical thinking and the resultant analysis became more sophisticated (see the summary of contributions to PER given in Chapter 7).

The first section (6.1) brings to the fore the role of *transduction* in physics, both in the meaning-making practices of the discipline, and in the teaching and learning of physics. Section 6.2 goes on to illustrate the ongoing theoretical development that I was engaged in vis-à-vis how I used this discussion analytically. Here I describe how the students that participated in Case Study (A), learnt in a conceptual way about a phenomenon that is not visible to the naked eye—the Earth's magnetic field—using a probeware tool, the iOLab, whilst at the same time also showing semiotically how they were coming to appreciate a key disciplinary affordance of an abstract mathematical tool: the *movability* of a Cartesian coordinate system.

Section (6.3) presents results from Case Study (B), in which South African first-year students were given the same task designed for Case Study (A). The discussion focuses on one possible hindrance to students coming to deeper understandings of physics concepts, which is the over-valuing of the use of mathematical resources in physics learning. The final Section (6.4) presents my synthesis of the theoretical development that followed my work, particularly the inclusion of transduction, which went on to play a central role in my proposed new definition of representational competence. By way of illustration, this section shows how a pair of students practised and moved towards representational competence in one semiotic resource system, graphs, in 1-D kinematics.

Having taken the reader through the story-line of this chapter, and in so doing illustrated that the formulation of the results for my thesis research questions would necessarily draw from across all of the papers that form an integral part of this thesis, I end the chapter by listing the research questions again together with a succinct answer for each of them. Associated with all of my work are contributions that I have made to the field of PER. These are listed separately in Chapter 7.

Before I continue I need to make the following statement regarding re-use of parts of the descriptions given in my five papers. This is to avoid any misunderstanding arising out of the re-use of already published text vis-á-vis so-called self-plagiarism. Since much of what is presented in this chapter has already appeared in papers that constitute the core of my thesis work, I re-use verbatim, portions of writing and illustration that appear in these papers. I do this with the permission of my co-authors. Figures and tables used in publications are referenced in the figure and table captions. Sections that verbatim include significant portions of published work are referenced using footnotes to these section headings. This is not done in terms of page numbers, but in terms of the particular paper (Paper I, Paper II, and so on).

6.1. Transduction in physics and physics education[31]

The role of transduction in physics and physics education is discussed at length in Paper III, pp. 16–20. Part of that discussion is repeated here for two reasons: first to show the reader that it represents my answer to my first research question, and second, to make it clear that the resultant description was not only a result of my reflection on the question, but that the description that follows was constituted from discussions that I had together with three physicists who were or had been actively involved in the research, and refined from discussions that followed my presentation of it to my UUPER colleagues.

I begin with a social semiotic exploration of the function of physics devices and the role transduction plays in their operation by drawing on the data and multimodal analysis from Case Study (A). Before proceeding I need to remind the reader that I am using Bezemer & Kress (2008) to characterize transduction in terms of the movement of semiotic material from one semiotic resource system to another. This is because I wish to highlight that moving from one semiotic system to another is not about learning to translate between the contents of the two systems. Rather, when semiotic material is moved from one semiotic system to another, a number of changes in visible signification occur.

[31] Paper III

Here, most importantly for the work I present in this thesis, the meaning potential of the transducted material is changed. And in this change both loss and gain occurs. For an everyday example, consider the simple sentence "The man moved out of the way". From the written content of this sentence, it is not possible to know which way the man moved, nor how large that movement was. Transduction into a diagram necessitates making these aspects visible by adding information (it is not possible to retain the ambiguity about how the man moved). However, at the same time it is probably no longer possible to see that the person who moved was a man (in drawing the diagram we most likely assumed that the person's gender was unimportant for the movement).

6.1.1. The role of physics devices from the viewpoint of social semiotics

The initial analysis of the student engagements from Case Study (A) demonstrated the fruitfulness of using a social semiotic multimodal perspective for analytically exploring the trajectory of interactive learning in a laboratory setting. Case Study (A) also highlighted how useful the iOLab device was in terms of the disciplinary and pedagogical affordances it could be used to evoke. In particular, the automatic, in-the-background, shifting of meanings, which the device system can perform enables users to see phenomena that would otherwise be imperceptible to them.

The ultimate goal of the discipline of physics is to model the behaviour of the universe and its contents in ways that make accurate predictions possible. Part of this process involves making sense of data. This can be seen as making interpretations of semiotic material, that is, treating the data from a phenomenon as being signs that originate from that phenomenon. The making of signs is central to any social semiotic perspective on meaning-making (see for example, Kress & Van Leeuwen, 2006). This starting point was critical in analysing the role of devices in physics communicative practices. The outcome of this analysis is a completely new way of viewing the role of devices in physics, and as such is a major theoretical contribution of this thesis. Further, this new perspective was leveraged to unpack, through the lens of the conceptual framework, the role that physics probeware tools may play in the teaching and learning of physics, another new contribution made by this thesis.

Historically, physicists were limited to direct observation—that is, they could only work with the input from the environment that was directly available to their senses. Today however, most experimental physics is carried out by means of mediated observation, that is, by using apparatus of some sort. Physicists have at their disposal a vast array of devices specifically developed to help them interpret environmental input. At the most basic level these physics devices can fulfil three functions—they can intensify, filter and transduct the meaning potential in the environment.

Intensify

The first function a physics device can perform is to intensify a signal in order to make it available to our senses. An optical telescope is an example of a tool that intensifies a signal; for example, enabling physicists to see the rings of Saturn that are not visible to the naked eye.

Filter

The second function a physics device can perform is to select the input of interest. This process can be used to separate out certain input from other unwanted information. One everyday example is the way that polaroid sunglasses allow us to see the bottom of a swimming pool by suppressing the light reflected from the surface of the pool.

Transduct

The third function a physics device can perform is to transduct. Devices that transduct have been designed to receive environmental input in a form not available to our senses and change it to one which is. One well-known example of this function is the Geiger counter for detecting radioactivity—it transducts information about invisible radiation to an audible click—the more frequent the clicks, the higher the level of radiation.

The majority of physics devices actually perform a combination of these three functions, often in sequences or chains.

Interpreting the environment

In order to better understand the transduction carried out by a physics device it is useful to consider how humans make meaning from their environment without a device and then in turn communicate that meaning to others. In Figure 6.1, an individual sees marks on the ground. This individual already has a clear idea about what a deer is, the way it looks, its habits, etc. So, when this person sees the marks, these are interpreted as deer tracks—signs that a deer is present. From a semiotic viewpoint, these tracks are interesting because although they are quite clearly a sign of a deer, there is no intentionality in this sign making—the deer was not attempting to communicate anything through its tracks. Meaning is created solely by the interpreter.

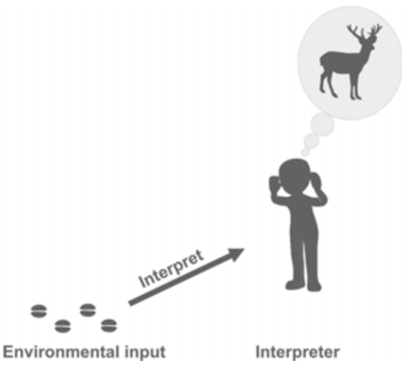


Figure 6.1. An individual making meaning from environmental input. (Paper III, p. 17)

Clearly this is always the case with signs—strictly speaking, meaning does not inhabit the sign itself, but rather is always assigned 'on the fly' in the process of interpretation.

In social semiotics we have become accustomed to dealing with communication *between* individuals. Here, it is quite usual to talk about the *interests of the sign maker* and this is clearly particularly pertinent in educational settings. In a given social setting, an individual makes a sign by first deciding which aspects of an 'object' are relevant to communicate. The individual then chooses between a range of available resources within the social setting, selecting a resource deemed apt to represent some of the pertinent aspects of the object. Note that this selection process is often tacit; however, analysis of the resources used still has the potential to reveal the interests of the sign maker, even though the sign makers themselves may be unaware of the choices that they have made (see for example, Kress & Van Leeuwen, 2006). The reader is here referred to Section 3.4.5 in which the selection of appropriate semiotic resources, which makes available disciplinary relevant aspects as learning goals for a particular task, is discussed.

Figure 6.2 depicts a system of meaning-making between two individuals employing a single sign—the word 'deer'. As in Figure 6.1, the environmental input is interpreted by the first individual, but now it is transducted to the word 'deer'. This spoken word is then interpreted by the second individual who has not seen the original tracks in the environment. Notice that there is always ambiguity and incompleteness in both the transduction and in the interpretation of the transducted sign. For example, it can be imagined that the original environmental input may well have been interpreted by the first individual as a sign of a range of aspects, such as the kind of deer, size, direction of movement, time since the tracks were made, etc. This meaning is not transducted into the word 'deer'. Similarly, the simple word 'deer' itself is ambiguous and can be interpreted in a number of ways. This has been denoted in Figure 6.2 by the different kinds of deer envisaged by the two individuals.

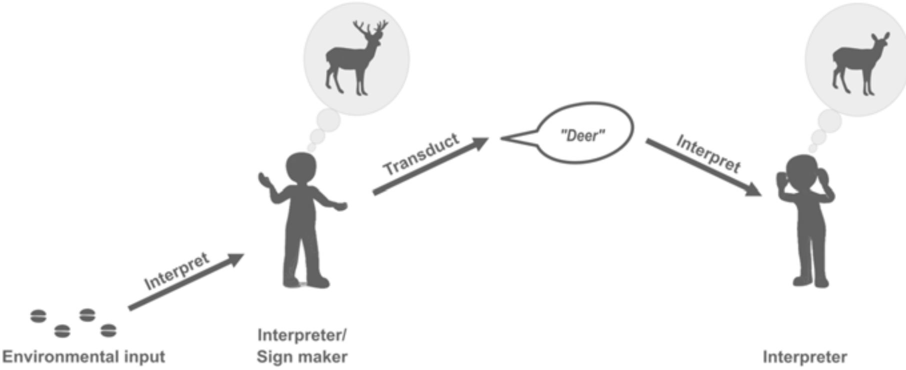


Figure 6.2. Transduction of visual environmental input to a spoken word, which is then interpreted by a second individual. (Paper III, p. 18)

Transduction to one sign alone can never mediate a full understanding of the original environmental input. Rather, a multimodal ensemble of signs is usually needed that leverages the generic affordances of different semiotic systems in order to approximate to the original environmental input. Meaning-making is more likely to be successful (and require fewer signs) if the sign maker and the interpreter have shared experiences and are from the same social group. In such cases there will probably be a shared understanding of the particular interests of the group and the *provenance* of the signs produced, i.e. what they have been used to represent in the past (Mavers & Oliver, n.d., cf. Airey, 2014). In this respect, the interests of the sign maker are not totally unknown, the provenance of the signs and the interests of the social group mean that sign making and interpretation is a far from arbitrary process. However, the sign maker can never be truly certain that the intended meaning has been accurately interpreted, nor can the interpreter be fully confident that the understood meaning was indeed that intended by the sign maker (cf. the notion of language games in Wittgenstein, Anscombe, & Wittgenstein, 1963). This is because the meaning of a sign is not fixed, but rather can be thought of as a flexible resource for meaning-making—meaning subtly shifts each time a sign is (re)produced (Van Leeuwen, 2005). With this analysis, it is easy to understand why novices in a discipline such as physics, where much of the implied meaning potentials of semiotic resources are tacit, may have difficulties in accessing the embedded ideas embodied by the discipline-specific signs chosen by experts to communicate disciplinary knowledge. The suggestion here is that the more frequently novices are immersed in authentic communicative practices *with each other* under the *guidance of experts*, the quicker they will become fluent in the ways in which the discipline has come to use its semiotic resource systems.

Within the conceptual framework used in this thesis, and the social semiotic framework developed and proposed (see Section 3.4), it must be pointed out that in physics (and science in general) we have an interesting, specialised form of the meaning-making system described in Figures 6.1 and 6.2. In physics, devices have been purposely designed to generate specific signs from environmental input. Here a decision has already been made about which aspect or aspects of a phenomenon are of interest. Thereafter, a device has been purposefully created in order to detect these aspects and intensify, filter and/or transduct them. In Figure 6.3, for example, environmental input that is not available to the human senses (in this case an X-ray source from space) is first transducted by an orbiting telescope to a graphical readout. This graphical readout is then interpreted in terms of two stars rotating around each other in a binary system. The physics community has not only decided which aspect or aspects of the phenomenon are important, it has also decided how the signs created by the device should be interpreted (cf. the discussion of the provenance of signs in the previous paragraph). This means that compared with meaning-making between two individuals, the possibilities for meaning-making with devices within the discipline of physics are extremely constrained. However, it is this very restriction of possible meanings which allows physicists to make such powerful knowledge claims (see Ainsworth, 2006 for a discussion of the constraining and complementary roles of resources[32]). For example, in Figure 6.3 the input from the environment has a myriad of possible meanings; however, the sign that is produced by the device is narrowly defined and carries a specific meaning for the discipline that is relatively unambiguous. Notice that it is the device that creates the sign from environmental input, and therefore, semiotically, the design of the device itself tells us in a much less ambiguous way about the interests of the *device maker*, that is, the *interests of the physics community*.

[32] It should be acknowledged here that Ainsworth (2006) refers to cognitive resources in her description of their constraining and complementary roles. However, the analysis shows that transduction, in the way it is used for the thesis, possesses these same functions in the meaning-making that occurs between individuals when signs have to be selected to communicate ideas.

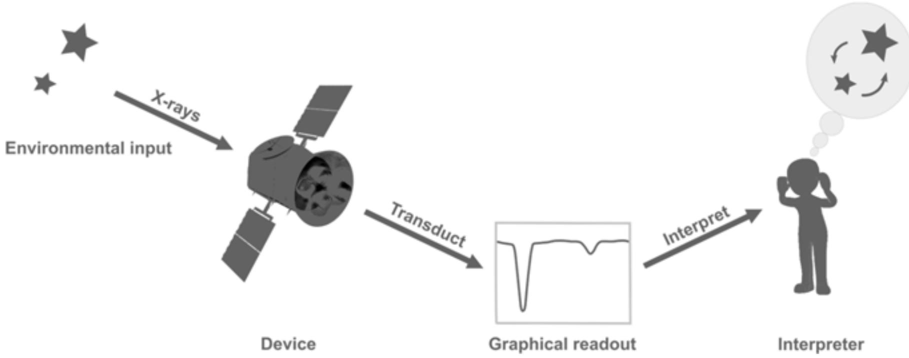


Figure 6.3. Transduction with a device in physics. (Paper III, p. 18)

Of course not all physics devices have been designed for the express purpose of producing a sign by intensifying, filtering and/or transducting a pre-existing signal from the environment. Clearly, many physics devices also produce signals that are sent out into the environment to generate a response. Nonetheless, the response signals received will still be intensified, filtered and/or transducted by a device and the signs so produced will still be interpreted following the praxis developed by the physics community.

So, transduction of environmental input represents one of the three main ways in which meaning is made using a device in physics. Clearly, however, for this kind of meaning-making to be successful in the teaching and learning of physics, students will need to come to understand two things: the interests of the physics community with respect to the phenomenon at hand, and the particular ways in which the community has decided that the signs generated by the device should be interpreted i.e. the disciplinary affordance of the device—see the discussion in Section 3.4.4, Airey (2015), and Airey & Linder (2017).

Of course, standard physics-specific representational systems such as graphs—as in the example in Figure 6.3—, are often the chosen output of devices. Students need to learn how these transducted signs (as disciplinary semiotic resources) should be interpreted to meaningfully re-/construct, for themselves, the physics concepts which the physics community has identified to be of relevance for work in a specific area. This point is important for the discussion in Section 6.4 about the development of students' representational competence in working with semiotic resources. Further employing this thinking, it is critically important for teaching and learning in physics, that the disciplinary affordances of devices are meaningfully connected with the disciplinary affordances of the other pertinent physics semiotic systems. If this is not done, there is a distinct risk for students exhibiting discourse imitation (see Sections 3.4.2 – 3.4.3).

In Section 3.4.4 the disciplinary and pedagogical affordances of semiotic resource systems were discussed. In the following two subsections, 6.1.2 and 6.1.3, these two terms are leveraged to describe the role of transduction in the teaching and learning of physics with regard to the incorporation of physics devices and tools in disciplinary and learning activities. Case Studies (A) and (B) involved students learning about the Earth's magnetic field. The novel-for-physics theoretical lens—transduction—was therefore trained on two devices, a standard terrestrial compass and the iOLab (a probeware tool with a 3D magnetometer sensor), to establish how the usage of these devices could be analysed in terms of understanding the phenomenon of magnetic field.

6.1.2. The compass—a transduction device for magnetic field

Although migratory birds can sense the direction of the Earth's magnetic field and use it for navigation, the same cannot be said of humans. As far as we know, humans cannot sense magnetic field without some sort of transduction device. Historically, the effects of magnetic fields on naturally occurring magnetite—or lodestones as they were called—had been known for thousands of years. The first compass-like objects are thought to have been constructed as a device for divination by Chinese geomancers in the second century BC, by fashioning a spoon-like object from a lodestone (Needham, 1962). The 'handle of the spoon' always mysteriously pointed south. The modern magnetic compass is simply a development of this idea and is in essence a transduction device for the magnetic field, however it is important that we remember the interests of the device maker here. Clearly, modern compasses have been designed for navigation across the surface of the Earth. This means that compasses do not actually show us the true direction of the Earth's magnetic field, rather they show us the direction of the *component* of the magnetic field along the surface of the Earth, i.e. its terrestrial projection. The actual direction of the magnetic field depends on where we are on the surface of the Earth. The Earth's magnetic field can be modelled in terms of a large imaginary bar magnet within the Earth approximately aligned from pole to pole[33] (Figure 6.4).

[33] Actually, the magnetic dipole is offset relative to the Earth's rotation axis by approximately 11 degrees, so that the geomagnetic equator (0° Main Field Inclination) over Africa in fact lies north of the Equator. Factoring in the South Atlantic magnetic anomaly, it is interesting to note that the inclination of the magnetic field over most of South Africa is similar in steepness, but opposite in direction to that in Northern Europe.

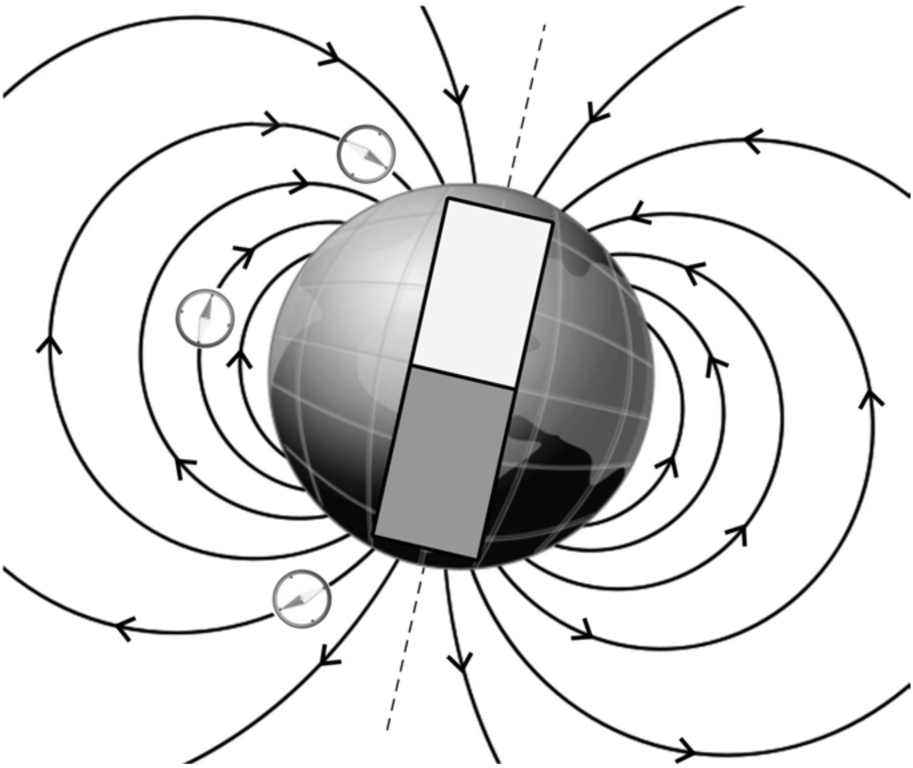


Figure 6.4. The Earth's magnetic field modelled in terms of a large bar magnet within the Earth. Notice the compass needles are aligned with the imaginary field lines. (Paper III, 2019, p. 20)

As can be seen from the imaginary field lines in Figure 6.4, at the geomagnetic equator (about 11° North over Africa), the magnetic field does indeed point along the surface of the Earth, but as we move north, the direction of the magnetic field points more and more steeply into the Earth. Similarly, as we move south from the geomagnetic equator, the magnetic field points more and more steeply out of the Earth. Because of this, compasses are often balanced with small weights when they are manufactured so that they point along the surface of the Earth. Compasses are therefore often designed to function at a particular latitude. In terms of the foregoing discussion, compasses manufactured in this way perform two of the functions of physics devices described earlier; they *transduct* magnetic field to a compass needle that we can see and they also *filter* out the vertical component of the magnetic field so that the needle points along the surface of the Earth. In physics, however, we are usually interested in the actual magnetic field in three dimensions. Thus, whilst the compass may have high disciplinary affordance for geographers it actually has low disciplinary affordance for physicists, because it does not show the true direction of the magnetic field.

6.1.3. The iOLab—a transduction device with high disciplinary and pedagogical affordances

In light of the preceding discussion, a new probeware tool for physics teaching, the iOLab, presented an interesting point of comparison. Applying the conceptual framework used in this thesis, an analysis of the functions of the iOLab revealed its particular usefulness for doing physics *and* teaching physics (i.e. it has high disciplinary and pedagogical affordances).

The iOLab and its potential usefulness in physics laboratory work were suggested in Section 5.2. Physicists and students may use the device to investigate a wide range of physics phenomena—for example, built into its sensor-box are an accelerometer, magnetometer, gyroscope, light intensity sensor, atmospheric pressure sensor, and temperature sensor.

With the magnetometer selected from the iOLab-computer interface screen (see Figure 5.1), the strength of the magnetic field is measured in three dimensions (Cartesian components). The iOLab system transducts this information to a graphical display in real-time producing three colour-coded plots (see Figure 6.5).

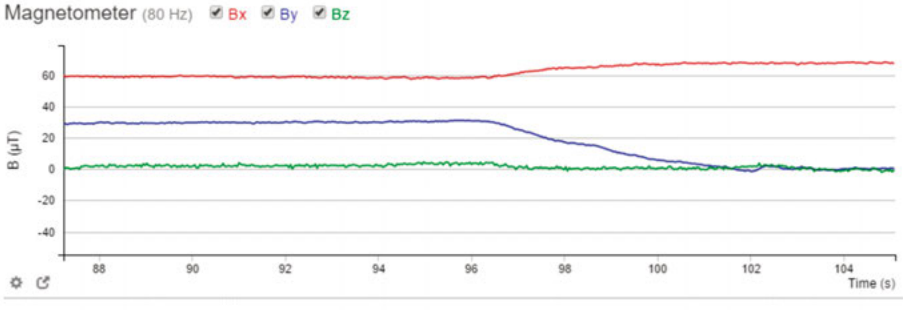


Figure 6.5. A screenshot of the transducted, three-component-plot of the magnetic field on the computer screen as the iOLab is moved. (Paper I, 2018)

Returning to the discussion in 6.1.1, the physics device here, the iOLab, has detected an invisible phenomenon present in the environment, the magnetic field, and transducted this input to a sign which may be interacted with, the three-component graph. Detecting the magnetic field, and producing precise measurements of the magnetic field strength in three dimensions, is therefore a generic disciplinary affordance of this tool. Using this information an expert can quickly work out the total field strength as well as the direction of the total field vector (using their basic mathematical knowledge of coordinate systems). For the teaching of physics, more specifically creating opportunities for students to gain access to the disciplinary relevant aspects of physics concepts, the iOLab then also offers generic pedagogical affordances. The iOLab sensor-box may be manipulated by students, leveraging their proprioception, and while doing so they can see the effects of this movement immediately on the screen (see Figure 6.5 where the sensor-box was rotated around the z-axis, resulting in the y-component of the field becoming zero). This feature was leveraged in the design of the learning task—students can by manipulating the sensor-box determine the direction of the magnetic field in the environment, and if they know how to interpret the graph (the sign), they can create an image of what the field 'looks like'.

In summary, the iOLab device has high generic pedagogical and disciplinary affordances; these need to be leveraged for physics teaching through the creation of a concrete learning task. Using the terminology of the conceptual framework, the iOLab is an example of a multi-purpose, disciplinary-focused, transduction device where the interests of the device maker are pedagogical—that is, the device has been made with the intention of teaching physics whilst doing physics. In Figure 3.2, under Section 3.4.4, the iOLab may be placed firmly in the purple area of the diagram, as one of the rare physics tools that possess the potential for both high disciplinary and high pedagogical affordances.

6.1.4. Selection and analysis of video data for full multimodal transcription

The learning task, the student cohort, the classroom setup and other practical measures taken for conducting Case Study (A), were discussed in Chapter 5.

Analysis started while the data collection was occurring. At that time, one of the facilitators directed the attention of the research team to one particular student pair where interesting meaning-making events and learning appeared to be taking place. When the video material from all six pairs were reviewed, the initial observations of the facilitator were confirmed—it was apparent that not only did learning take place with this particular pair, the students also articulated their learning at several stages. The interaction of this pair was therefore chosen for further investigation because it clearly illustrates the role that transduction can play in the teaching and learning of physics. This particular interaction consisted of approximately 80 minutes of video data, of which just under 40 minutes was transcribed and analysed for this study. The complete multimodal transcript of this engagement is provided in Appendix A.

Only transcript extracts which are of direct relevance to the findings of this thesis, in the area of transduction in physics, are provided in the following section. The accompanying diagrams are empirical illustrations of the conclusions about the multimodal sequence that occurred during the task.

The transcript extracts are presented in a way which seeks to best present the students' usage of the multi-modal ensemble of resources, as well as recording and interpreting students' and facilitators' multimodal interactions (see Chapter 5). Variation in text formatting (italics, bold), and different brackets (normal, square and curled) are used to distinguish different features of the engagement. These stylistic features employed in all transcripts in this thesis are listed in the following points:

i. Time stamps provide an indication of the placement of the selected excerpt within the entire sequence—the reader is encouraged to check this against the full transcript in Appendix A.
ii. Actual transcribed speech by participants is given in italics.
iii. The two students in this sequence are given the labels S1 and S2, and the facilitators are given the codes F1, F2 and F3.
iv. Actions of participants are given within square brackets, transcriber additions or comments about talk and actions are added in normal parentheses, and other synchronous and asynchronous multimodal activity, e.g. the position of the iOLab device and axes orientation, are recorded inside curly brackets. Actions and multimodal activity given below speech lines indicate coordination with that speech.
v. Three dots before and after speech lines indicate pauses and/or simultaneity with preceding or subsequent speech.

6.1.5. Results and discussion: the iOLab, transduction and the leveraging of pedagogical affordances

The introductory sequence lasted approximately 8 min 35 sec, in which one of the facilitators (F1) introduced the task. This time was also used to calibrate the iOLab system.

Given the open-ended nature of the task design, the students in all six pairs were at first uncertain about what to make of the collection of resources in front of them. The following transcript extract typifies this initial stage of the learning sequence.

Extract 1 <Time [minutes:seconds]→ 09:30 – 10:18>

S2: *We should be showing the direction of this…*
[S2 grabs cut-out red arrow]

S1: *I don't know, how do we read that, how do we know that?*
[S1 looks at screen]

S2: (reading instruction sheet) *"...and to fix the arrow that represents the direction"*
[S2 chuckling and looking at screen]
{holds and dangles red arrow in front of screen}

S1: *Ohh, I guess, I don't know, mmm, what happens if we move it. Oh S#!t, look at that ...*

[S1 grabs iOLab and rotates it while looking at screen, …both look at screen]

S2: *chuckles* (hah, hah, hah)

S1: *Holy crap, holy crap ... Ummh, yeah, moving it changes it of course, so I guess we could figure out by the amount...*

S2: *No, I guess…*

[S2 takes hold of iOLab and rotates it]

S1: *You see the blue line went up to the top*

[S2 is still rotating iOLab]

[S1 points at graph on screen]

S2: *Yeaah, ok.*

S1: *Yeah, I don't really know what this tells us.*

However, within a minute or less of engaging with the iOLab, the students started making connections between the sets of resources. The reader is encouraged to refer back to Figure 5.? in which the student tests various positions and orientations of the iOLab box with reference to the graphical display on the computer screen. In doing this he is leveraging his natural proprioception (that is knowledge of the position of his own hand without the need to look at it), and also exploiting one of the key pedagogical affordances of the iOLab device—the real-time link between changes in the orientation of the device and the immediate representation of the device's measurements on the graphical display (three coloured lines on the graph representing the components of the magnetic field in three dimensions).

By designing the iOLab device to be hand-held and equipping it with sensors that give access to physics phenomena, the physics community has afforded students the opportunity to directly engage with physics using their own body. The iOLab's aptness for teaching physics—that is, its pedagogical affordance—is contained in the fact that the system facilitates seamless shifts between disciplinary resources (in this case a graph of a three-dimensional field) and everyday resources such as the senses (in this case proprioception). However, the iOLab also has high disciplinary affordance—the device can be used to actually do physics. Thus the transductive nature of the iOLab device made it possible for students to start to "experience" the Earth's magnetic field—an otherwise invisible and unchanging field in the room—by simultaneously observing the changes in screen output as they "felt" the changes in orientation of the iOLab in their hand.

As the learning sequence progressed, the student pair devised a strategy for obtaining the direction of the magnetic field by first making one and then two of the graphical readouts show zero on the screen. At this point "all" of the magnetic field is shown by the third readout and thus the iOLab at this stage must be in such an orientation that the third axis is aligned with the magnetic field. In Figure 6.5 the *x*-component (the red plot) is made to contain all the field information (its direction indicated by the printed axis on the sensor-box) by keeping the *z*-component zero and then rotating the sensor-box around the *z*-axis until the *y*-component is also zero. The students quickly learned to "feel" their way to this result by observing the real-time readout as they moved their hand.

Facilitator's use of transduction

Understanding the open-ended laboratory task involved a great deal of disciplinary knowledge that is not immediately accessible to the novice. Students were learning about an invisible phenomenon (magnetic field), by using a physics device they had never met before (iOLab) to transduct meaning to a resource (the graphical display on the screen) which involves an understanding of the orientation of an invented, imaginary coordinate system (the three axes at right angles to each other that are printed on the iOLab – see Figure 5.?). Despite the students having now devised an appropriate strategy to determine the direction of the magnetic field, it was clear at this stage that they had not been able to grasp all the disciplinary meanings and transductions that had occurred in their coordination of the resources. The second extract which follows illustrates this.

Extract 2 <Time→ 22:22 – // – 24:20>

G: *You want z- to be zero?*

S1: *Yah, I'm trying to get both of them zero at the same time.*

[S1 now takes hold of device on top of box and looks at screen; G peers over outstretched arm of S1 at screen.]

S1: *Isn't that z-? I don't understand, that should be z-.*

[S1 moves device towards him slightly and looks at screen]

{The +*z*-axis on the device is in a line away from B, the *y*-axis is still pointing up, and the *x*-axis points to his left}

G: *That should be z?*

S1: *It's not moving.*

// a short while later:

G: *… but if, if … if we tilt it this way, then z- changes, see …*

[*G* swivels the device about the *x*-axis]

{*x*-axis pointing perpendicular to field which gives a zero reading for the *x*-component on the graph}

S1: *Yeah*

G: *If I put it on the horizontal… way; see now it gets, x, no, y is zero.*

{At end of G's manipulation, the device is held so that the *y*-axis is pointing almost perpendicular to the magnetic field, i.e. almost horizontal}

S1: *But how?*

G: *But why is it, why is y- zero?*

[G looks around class (for assistance?), smiles, then looks directly at camera]

{G is still holding device in position where y-value is zero}

S1: *I don't know… by my logic it shouldn't be working like that, or I don't know ...*

G: *{laughs}…could we get help, ...see… he explains ...OK.*

[G points to a facilitator across the room]

{G looks around class (for assistance?), smiles, then looks directly at the camera, still holding the device in position so that *y*-value is zero.}

The students had simply implemented a trial-and-error approach in which they manipulated the iOLab device until they had only one non-zero component on the screen. Empirically, they had not yet coordinated all the resources to make physics meanings—for example they had not referred to or used the printed axes on the box in any direct sense-making way. The data shows that the facilitators also spontaneously leveraged their bodies and hands to illustrate the transductions of meaning between these various systems of resources. (An example of this can be seen further on in this chapter in Figure 6.9. There we can see a facilitator using his outstretched arms to help students make the link between a zero-component on the screen and the printed axes on the iOLab).

Transduction to a persistent semiotic resource

At this point one of the facilitators proceeded to ask the student pair a series of exploratory questions in a Socratic dialogue. When asked to explain their strategy, the students had difficulties at first:

Extract 3 <Time→ 26:26–26:57>

F1: *OK, ... good, now that you have the blue line; so what's the blue line? It's the y- right?*

[F1 points at screen, then comes closer to screen]

S1: *Yeah*

G: *Yes.*

F1: *So the y one, No, actually, no… the red one is zero right now, I'm sorry.*

[F1 corrects himself by pointing at screen]

S1: *Yeah, ... or close to zero it is.*

F1: *…close to zero, yes. So what does that mean for the field; in which direction is it **not** (emphasis) pointing?*

S1: *Umm…*

F1: *You've eliminated one, one family of directions ... which family would that be?*

[F1 uses hands in encircling motion ("family of directions")]

G: *MM-mm ... the horizontal…*

F1: *All the horizontal ...or just ...*

S1: *Wouldn't it be this way?*

[S1 moves hand back and forth in line of x-direction with index finger pointing in $+x$-dir'n]

F1: *Yes, exactly…*

G: *…yeah, yeah, true.*

The facilitator helped the students fix the cut-out arrow to show the direction of the magnetic field that the students had found. After about thirty minutes of working with the iOLab and the associated systems of resources, most of the students in the laboratory had been able to determine the direction of the Earth's magnetic field and had fixed the provided cut-out red paper arrow to a vertical surface to denote this direction. Most strategies were along the lines described above. Figure 6.6 powerfully illustrates the general agreement and alignment of the red arrows pasted individually by the groups of students.

Figure 6.6. The cut-out red arrow serves as a persistent placeholder for previously transducted meanings. (Paper III, p. 24)

As a persistent semiotic resource, the red arrow now 'became' the magnetic field for the student groups, that is, it served as a *placeholder* for all the multimodal meaning-making that had gone on up until this point. The importance of transduction of a range of temporal coordinations of semiotic resources to a single, persistent placeholder cannot be over emphasised. Having found the direction of the magnetic field, further meaning-making was facilitated by having a permanent visual representation of the earlier coordinations of resources—the students did not need to continue to hold the iOLab device in the orientation they had discovered, but could interrogate the arrow instead. This tangible, visual resource had been deliberately chosen by the research team as the *visual site of display* for disciplinary knowledge about what physicists know about the Earth's magnetic field at specific locations—the arrows pasted by all the groups created a visual map of the imaginary magnetic field lines in the room. In this way, students could observe that, even though each group may have used different strategies and made choices for themselves (about iOLab orientation and therefore that of the set of axes, etc.), the physics (i.e. the direction of the Earth's magnetic field in the laboratory) was not dependent on these individual choices.

The cut-out arrow now became a persistent representation of the whole chain of transductions which had occurred thus far in the sequence. Going forward, the arrow now also functioned as a *coordinating hub* for further meaning-making—see the discussion in 3.?, Fredlund, Airey, & Linder (2012), and Fredlund (2015). Coordinating hubs are (usually persistent) representations that appear to be central to a given *critical constellation of semiotic resources*—see the discussion in 3.?. Coordinating hubs function as a central resource around which meaning-making with other persistent and non-persistent semiotic resources can be arranged.

Now, with the arrow fixed by holding the iOLab box in a particular orientation in relation to it, the facilitator could ask the students to reflect on the box's position and the relationship between the arrow, the axes printed on the box and the graphical readout on the display. The following transcript extract provides one instance demonstrating the coordinating function that the persistent semiotic resource (the arrow) filled in the learning sequence:

Extract 4 <Time→ 31:59 – 32:20>

F1: *So, if you want to **align** (emphasis) this vector to this vector, what should you do?*

[F1 points in order at axes labels (printed on iOLab) in direction of +*z*, then at red arrow]

S2: *Ah-hah! This way ... ah, OK,*

[S2 grabs iOLab (smiles broadly) and holds device with {+*z* pointing up at an angle directly opposite to dir'n of red arrow}]

[S1 extends hand towards device (but S2 grabs it first), then withdraws hand to mouth and watches screen]

F1: *Yahh…*

[F1 looks at S1 (to check if S1 also gets it)]

S2: *Yeah, ah-hah, [indistinct] it's a negative [indistinct] because it's pointing this way and ...*

[S2 looks at screen to look at value for B_z; explains negative screen value for *z*- with hand and finger first gesturing along dir'n of red arrow (down at angle), then opposite]

S1: *Yeah*

[S1 nods head up and down]

F1: *What if you flipped it around? It's positive?*

[F1 points at iOLab, and then makes a flipping gesture with right hand and two fingers in V-shape]

[S2 flips device about *y*-axis so that +*z* now points in direction of red arrow, looks at screen and smiles]

S1: *Yeah, it's positive 50.*

[B's right hand first over mouth (closed, loose fist); looks at screen and confirms *z*-value, right hand now first strokes hair over right ear lightly, then rests fingers against neck and chin, and starts pinching at cheek gently, touches ear etc.]

F1: *Makes sense?*

[F1 looking at S1 intently]

S1: *...Yeah.*

S2: *Mm-mm ... That's pretty cool. I mean that is cool.*

S1: *Yeah, ah yeah.*

Transduction to new resources

Earlier in this section, the students' initial incomplete appreciation of the meanings underlying the information displayed by the ensemble of resources they had coordinated was reported on. However, in the sequence after the fixing of the cut-out arrow, the students started spontaneously using *gestures* that they had *not used until this point*—the reader is here referred to Section 6.2 where these gestures are discussed in more detail. These new gestures were made in direct relation to the arrow. The arrow now appeared to function as a coordinating hub for bringing together the orientation of the iOLab and the readout on the graphical display. Students made expressions of understanding together with their new gestures—see Figure 6.7 and the 4th extract. Their demonstrated understanding was now tested by the facilitator who asked them to try different orientations of the iOLab box, eliciting explanations for the information displayed on the graph with reference to the axes and the arrow.

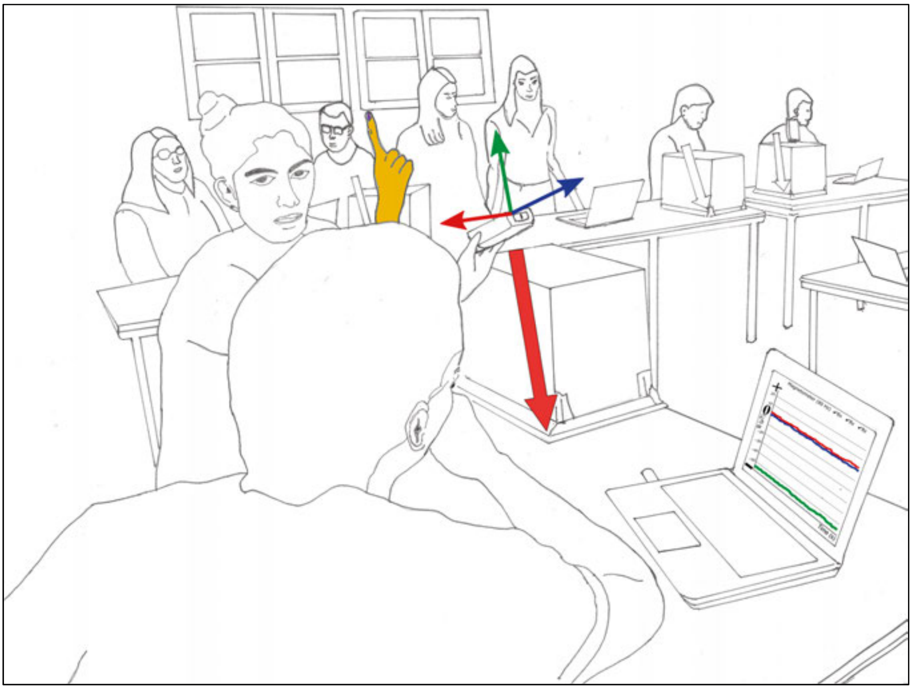


Figure 6.7. Introduction of a new resource (gesture). The red arrow functions as a coordinating hub (Volkwyn, Airey, Gregorcic, & Heijkenskjöld, 2019, p. 25). Notice that the arrow (the determined direction of the Earth's magnetic field in the room) is aligned opposite to the *z*-axis as indicated by the axes printed on the iOLab sensor-box, held by the student in place. Notice also the plots on the graph screen. (Paper III, p. 25)

Demonstrating an understanding of magnetic field

The students were set a task to locate the direction of the Earth's magnetic field, which without the transduction device would have been invisible to them. However, it was clear that with the red arrow now as a persistent representation of the direction of the field, the students had no problem in directly making reference to issues related to the magnetic field, and magnetism in general. Students asked questions related to what affects the magnetic field, how it "looks", and possible uses of magnetometer devices. It therefore seems that the students' newly gained understanding or appreciation of the phenomenon through the learning activity stimulated disciplinary appropriate and relevant questions. As a follow-up exercise, students leveraged their new understanding of magnetic field by using the iOLab to locate the steel beams in the concrete of the laboratory building. They simply rolled the iOLab sensor-box along the floor and correctly interpreted marked changes on the graph to the presence of a steel beam below the device.

6.1.6. Conclusions – toward answering the research questions

With reference to the role of transduction in physics, Case Study (A) started with a few initial research questions (Paper III, p. 21):

1. How do pairs of students leverage the pedagogical affordances of a physics device (iOLab) when working with an open-ended task [in the physics laboratory] to determine the direction of the Earth's magnetic field?
2. What stages can be identified in this process in multimodal terms?
3. What does a multimodal analysis of the students' coordination of semiotic resources suggest about the role that transduction can play in the teaching and learning of physics?

When it came to leveraging the pedagogical affordances of the iOLab, students were immediately able to use their own hand movements and proprioception to start making connections between the iOLab's orientations and the corresponding graphical output. Significantly, the students did not need to understand any of the underlying physics before they started to engage with the Earth's invisible magnetic field. They quickly found the direction of the field by implementing a trial-and-error strategy based on their physical experiences and interaction with the iOLab sensor box and system.

The students' engagement with the iOLab provides evidence to suggest that the device has both high disciplinary and high pedagogical affordances. This is quite unusual, for as Airey (2015) pointed out in his description of these two affordances, they are often in functional opposition – an increase in pedagogical affordance often lowers the disciplinary affordance of a semiotic resource and *vice versa* (see Section 3.4.4 and Figure 3.2 for a fuller description of this relationship).

Turning to the second research question, a description of the learning process in multimodal terms, the following stages were identified: the students quickly coordinated their talk, their proprioception of the position of the iOLab and the real-time changes in the graph to find the direction of the Earth's magnetic field. At this point the students were encouraged to use a persistent semiotic resource (the arrow) to indicate this direction. The arrow now functioned as a persistent *placeholder* for all of the meaning-making that had occurred up until that point. In effect, the arrow now *became* the magnetic field for the students and was used as such in their continued meaning-making.

As discussed earlier, under the heading 'Transduction to a persistent semiotic resource' Section 6.1.5, the arrow functions as a coordinating hub, where the critical constellation of semiotic resources necessary for an understanding of the Earth's magnetic field appeared to consist of the arrow (and the meaning-making that had gone into its positioning), the graph, the printed axes on the iOLab and the orientation of the device. At this point, the students introduced new semiotic resources (gestures) to help to explain their understanding. These gestures were also made in coordination with the arrow and its related resources. The introduction of new semiotic resources suggests that learning had taken place, especially since the facilitator was on hand to check the students' understanding.

When it comes to the role of transduction in the teaching and learning of physics, transduction is central to doing physics and is an inherent property of many physics devices—see the discussion in Section 6.1 where my conceptual framework was used as lens to reveal the centrality of transduction in physics and in the way that physics devices are designed to communicate meanings from environmental input). The analysis presented in Section 6.1.4 now revealed how transduction is also central to *learning* physics. Three distinct shifts in this learning sequence are identified. First, the iOLab transducts the meaning potential in the room (magnetic field) to a visual resource (graph). Next, the students transduct all previously made meanings to a persistent resource (arrow) which now functions as a placeholder for these meanings. Finally, students summarise their understanding by transducting meaning to new semiotic resources (gestures). Using the lens of transduction, it may be argued that there are a number of recommendations that can be made for lecturers about the use of placeholders and coordinating hubs, and the way in which transduction can be seen as a sign that learning has taken place.

Implications for the teaching and learning of physics

Planning a lesson

When planning a lesson, it is suggested that lecturers should consider the set of resources that students will need in order to construct the intended disciplinary meanings. Here, the range and type of resources is important. Too many resources will be difficult to coordinate, particularly if these resources are non-persistent. Can the coordinations of persistent and non-persistent resources be substituted by a persistent placeholder? Here, lecturers are advised to spend time thinking about what this persistent placeholder might be and when it should be introduced. Lecturers should also think about the role that this placeholder will play in meaning-making. Is there a need for a hub around which the resources can be coordinated, and if so, what might this coordinating hub be? For instance, in Case Study (A) the placeholder and the coordinating hub happened to be one and the same thing (i.e. the red paper arrow), but this will not always be the case.

Teaching a lesson

At the outset, lecturers should know which resources are necessary for the appropriate constitution of disciplinary knowledge (i.e. the critical constellation of resources). During the lesson, lecturers should be paying attention to the students' use of these particular resources and if a placeholder is needed, then the lecturer should make sure that it is used as intended. Similarly, if a coordinating hub is required then lecturers should be looking for evidence of this being introduced/used by students (cf. Fredlund et al., 2012).

The analysis suggests that lecturers should not expect students to understand disciplinary meanings directly. Even though students may have coordinated the correct semiotic resources in a disciplinary manner, this does not mean they now understand the physics involved. Students need time to interrogate the resources they have used and the coordinations they have made. Airey & Linder (2009) have described this process in terms of becoming fluent in a critical constellation of semiotic resources. When this fluency has not yet been achieved, they claim that students *imitate* disciplinary discourse, that is they use semiotic resources appropriately, but without an appropriate understanding of the disciplinary meanings they represent.

From a multimodal perspective, the findings lead to the suggestion that transduction between semiotic resources is both the means by which students and lecturers can notice when discourse imitation is occurring and the way in which students 'discover' disciplinary meanings for themselves. Here the role of the instructor is key, either to encourage and confirm correct transductions of disciplinary meanings, or to ask questions that help students notice that they may still not have grasped key issues in a disciplinary manner.

Thus, it is suggested that lecturers should be looking for student introduction of new semiotic resources. Here transduction is a sign that learning is taking place. The transduction to new semiotic resources fills two important functions: first, it allows students to demonstrate their learning, and second, and perhaps more importantly, it allows lecturers to check this learning. This is because of the complementary and constraining functions that transduction entails. As discussed at the beginning of Section 6.1, when meaning is transducted from one semiotic resource to another, information can be added or taken away. Thus, the signification in transduction can serve as a useful check of student understanding since disciplinary meaning must be coherent across all transductions.

Transduction devices in science teaching

Whilst the disciplinary affordance of transduction devices is clearly understood, (i.e. we know very precisely what function a particular device plays in science), a lot less is known about the potential pedagogical affordances of many devices currently utilised in the teaching and learning of science. Future work should explicitly examine the pedagogical affordances of such devices. For instance, what is it that makes a device suitable for teaching a particular kind of content? Should we require that devices have both high pedagogical and disciplinary affordance, (as in the case of the iOLab) or is it sufficient that devices have (say) only pedagogical affordance? In this respect, (Fredlund et al., 2014) and (Airey & Eriksson, 2019) have suggested the unpacking of semiotic resources with high disciplinary affordance to create resources with greater pedagogical affordance. This suggestion of unpacking clearly also applies to physics devices.

It is worth reiterating that one of the main pedagogical affordances of the iOLab is that it was possible to manually manipulate the device whilst simultaneously following a real time readout on a screen. Critically, this allowed students to 'feel' (so to speak) their way to the magnetic field direction. The potential for other devices to allow students a similar experience of other physics phenomena is something that is certainly worthy of further investigation.

6.2. Learning about abstract mathematical tools – the movability of coordinate systems[34]

From the perspective of learning about the movability of coordinate systems, Case Study (A) had the following initial research question (Paper II, p. 5):

> *In the context of the presented conceptual learning activity, how, without engaging in numerical calculations, can students come to experience and appreciate the movability of coordinate systems?*

The following discussion summarises how this initial research question has been addressed and answered. Drawing on data from Case Study (A), the analysis and findings presented in this section extend the fine-grained multimodal analytical description employed in 6.1 to show:

- that introductory physics students may initially conceptualise Cartesian coordinate systems as being fixed in a standard orientation,
- how this learning challenge can be effectively addressed by giving consideration to the role that experiences of variation play in learning (see section 3.4.5),
- how students can quickly come to appreciate a key disciplinary affordance of an abstract mathematical tool, that is the movability of a Cartesian coordinate system, and
- how a conceptual learning task in the physics laboratory—leveraging the affordances of a physics learning device, the iOLab—can move students towards an appreciation of coordinate system movability (a key disciplinary affordance of this mathematical tool for physics problem solving), without the need for calculation.

[34] Papers I & II

6.2.1. Challenges for students learning about and with coordinate systems

The students worked with a movable magnetometer with a printed-on set of coordinate axes to determine the direction of a constant field (the Earth's magnetic field). Learning how to appropriately select and use coordinate systems is central to physics modelling and problem solving. For example, a search of Institute of Physics (IOP) journals yields over a hundred thousand papers with the phrase "coordinate systems" in the title. Yet, in undergraduate physics, coordinate systems are known to present a number of learning challenges for students—see for example Sayre & Wittmann (2008), and Vega, Christensen, Farlow, Passante, & Loverude (2017).

Although the setting up of a coordinate system is essentially an arbitrary process, in textbooks Cartesian coordinate systems are typically presented to students in one particular orientation—x increasing to the right, with y usually pointing "up the page" (or z for 3D systems)—see Figure 6.8, and the discussion in the next paragraphs. Such standardised presentation may initially lead to students conceptualising that coordinate systems are always fixed in this particular orientation (Paper I).

Unlocking the power of coordinate systems for physics problem solving involves appreciating their *movability*. It is precisely this movability that often allows for the simplification of many complicated forms of physics modelling and application. Coordinate systems are not fixed but can be set up in any orientation we desire. Physicists typically use this property of coordinate systems and assign them in such a way so as to reduce complexity and thereby facilitate the solving of the physics problem at hand. A key component of the conceptual framework adopted for this thesis is the necessity of coming to appreciate the disciplinary affordances of semiotic resources to make learning possible. From this, it is suggested that one of the reasons for initial student difficulties with using Cartesian coordinate systems to solve physics problems may, in part, stem from a failure to fully appreciate a coordinate system's movability.

1) Up is more, right is more

Before ever learning about Cartesian coordinate systems in mathematics or physics at school students have had the experience of change in a broad range of quantities as either increasing from left to right, or bottom to top. Here it is argued that these operate as *p-prims*[35] for students, "*up is more*", and "*left to*

[35] diSessa (1993) theorised that students learn physics (and other disciplines) by appealing to their *sense of mechanism* of the physical world. Everyday experiences of the world are loosely structured into heuristics he called *phenomenological primitives* (abbreviated as *p-prims*). One example used in this paper is "up is more". diSessa argued that students draw on these heuristics when trying to make sense of physical phenomena.

right is more", in western culture.[36] The effect of these p-prims in producing 'alternative conceptions' and *transient learning challenges* (Fredlund, Linder, & Airey, 2015) should not be underestimated, even for university students.

2) Physics textbook depictions of Cartesian coordinate systems

As stated in the introduction to this sub-section, physics textbooks tend to depict Cartesian coordinate systems in standard ways. As an example of this practice, below is presented a quotation from an American Association of Physics Teachers (AAPT) reference textbook for college students applying mathematics as a tool for science work (the diagrams used to explicate the text are very similar to those in Figure 6.8):

> With Cartesian coordinates in two dimensions, you locate points by constructing a horizontal reference direction, called the *x* axis, and a vertical reference direction, called the y axis, […] The *x* distance, the abscissa, is always first, then the *y* distance, the ordinate. In the case of three dimensions, the coordinates are listed (*x*, *y*, *z*) and the graph looks like the corner of a room where two walls and a floor meet." (Swartz, 1993, p. 122)

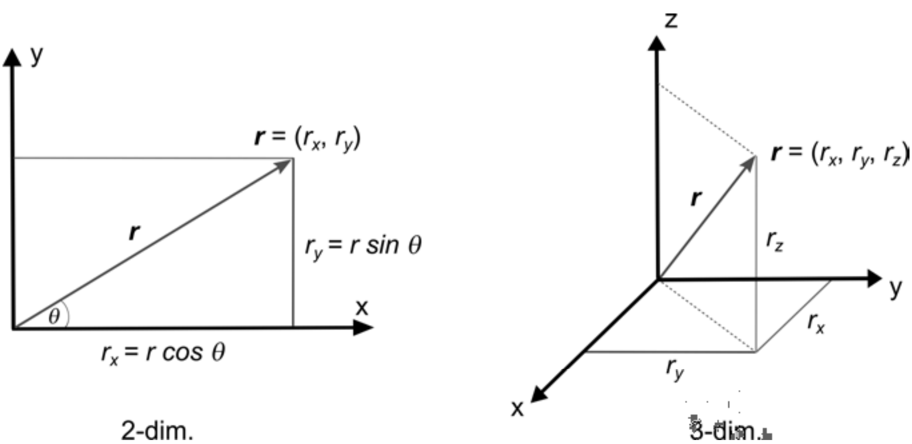


Figure 6.8. Standard depictions of Cartesian axes in physics and mathematics textbooks. (Paper II, p. 2)

Whereas for 2D frames the +*x* direction is coupled to horizontality and "to the right", for 3D systems the *x*-*y* plane is visualised as a horizontal floor of a room with the *z*-axis representing the "up" direction. In the absence of a discussion of the arbitrariness of the choices being made, it is argued in this thesis that these standardised depictions can reinforce students' perception of reference frames being fixed. This is problematic from the viewpoint of students

[36] These everyday experiences are reinforced by the design of scientific devices—for example, a thermometer has printed on its surface a temperature scale increasing in values from the bottom to the top—, and "sliders" on computer interfaces where up or to the right is always "more".

needing to learn the disciplinary ways of using coordinate systems, where movability is an essential disciplinary affordance that is regularly used.

The two factors stated above are most likely to cause difficulties if learning activities do not directly address the movability aspect. Some curricular materials do this purposefully, for example see Allie & Buffler (1998) and Reese (2000). An explicit focus on teaching the movability of coordinate systems seems to be key in helping students move towards a more disciplinary understanding and use of coordinate systems.

6.2.2. The role of variation – leveraging an invisible phenomenon to learn about an abstract mathematical tool

In the learning activity, the students worked with a physically moveable Cartesian coordinate system—they varied it—to find the direction of the essentially invariant Earth's magnetic field in their classroom (the task thus followed the variation design principle)[37]. At the same time, for the introductory level students involved in Case Studies (A) and (B), it is reasonable to assume that at the start of the activity many of them would be unaware of the direction of the Earth's magnetic field. The students utilised the 3D magnetometer sensor on the iOLab device to determine the direction of the Earth's magnetic field in their classroom and then used a cut-out paper arrow to present this direction visually. The students could move and turn the magnetometer in any way they preferred. However, some orientations naturally made the task easier than others. The direction of the field is most easily found by systematically rotating the device so that first one, and then two components of the magnetic field become zero. The third, non-zero component then gives the magnitude and direction of the field.

Whereas for the majority of physics problems, a fixed coordinate system is assigned in a way that best follows some change in physical properties; this is not the case with the activities in Case Studies (A) and (B). For here the power of the tasks given to the students is that these roles were reversed—the magnetic field that students wished to find the direction of was invariant and essentially the same for all the students in the classroom, whilst it was the orientation and movement of a given Cartesian coordinate system that was changeable. Since variation theory posits that students notice what changes, it is the movement of the coordinate system that the task directs students' attention to. This is in contrast to the 'static' implementation of the variation principle in the strategies espoused by Allie & Buffler (1998) and Reese (2000).

[37] See Marton (2015) for an overview of the extensive research done in the area of variation.

6.2.3. Coming to appreciate coordinate system movability

The excerpts selected in this section relate to the learning path the students followed to appreciate the movability of coordinate systems. The excerpts are presented in chronological order and exemplify important phases of the learning sequence. The full transcript is available in Appendix A.

NOTE: To be consistent in referring to the same individual for the thesis, the participant labels, F1 and F2 have been swapped as compared to the labels used in Paper II.

Excerpt 1 – Movement leads to change

Shortly after the students began the activity, they noticed that moving the sensor-box results in changes in the displayed plots (see Figure 5.1 under Section 5.2).

> *S1: Holy crap, holy crap ... ummh, yeah, moving it changes it of course, so I guess we could figure out by* the amount…

The students came up with explanations of the displayed components based on prior experiences, and tried to connect the information provided in the graphs to the task. However, the students were not yet able to make productive interpretations for the given task. Nonetheless, a short engagement with a facilitator towards the end of this phase resulted in the students finally linking the printed axes on the sensor-box to the three colour lines which plotted the Cartesian components of the magnetic field. The meaning of the graphical output still eluded them, however.

The next phase was typified by the students starting to make productive interpretations, which they did by leveraging the connections they had made and testing their ideas directly with the iOLab system—positions referenced to the printed axes compared to graph lines. In particular, they now explored the meanings of zero, positive and negative. To exemplify this phase, the following examples are presented.

Excerpt 2 – The meaning of zero

One of the first meanings the student pair tried to work out was why different component values became "*close to zero*" with the sensor-box placed in certain orientations. The transcript extract below represents a part of the interaction which took place between the students immediately before being joined by a facilitator (F2) and placing the sensor-box in the position shown in Figure 6.10.

> S1: *Umm, if x is zero it means there's no…*

S2: *So, so, it's all, it's all…*

[S2 makes up and down motion with arm]

S1: *There's no magnetic, … there is no reading from the magnet sensor in the x-plane, which means, uhh…*

F2 then came by and proposed a kinematics analogy. He extended his arms at right angles to each other to represent a set of coordinate system axes, and asked the students what the size of the *y*-component (his left arm) of velocity will be, if the movement is in the direction of the *x*-axis (his right arm). He then tilted his extended arms at a 45-degree angle (see Figure 6.9), and repeated the question for the new reference frame, with the motion now along the new *x*-axis (his tilted right arm). The students replied without hesitation that it will be "*still zero*", which indicates that they successfully recruited their knowledge of applying coordinate systems in kinematics. The facilitator also made the following comment at the end of this engagement with the student pair:

F2: *So you could reposition your own system… in a way that fits you, suits you*

[F2 makes swivelling gesture with right hand in front of his body]

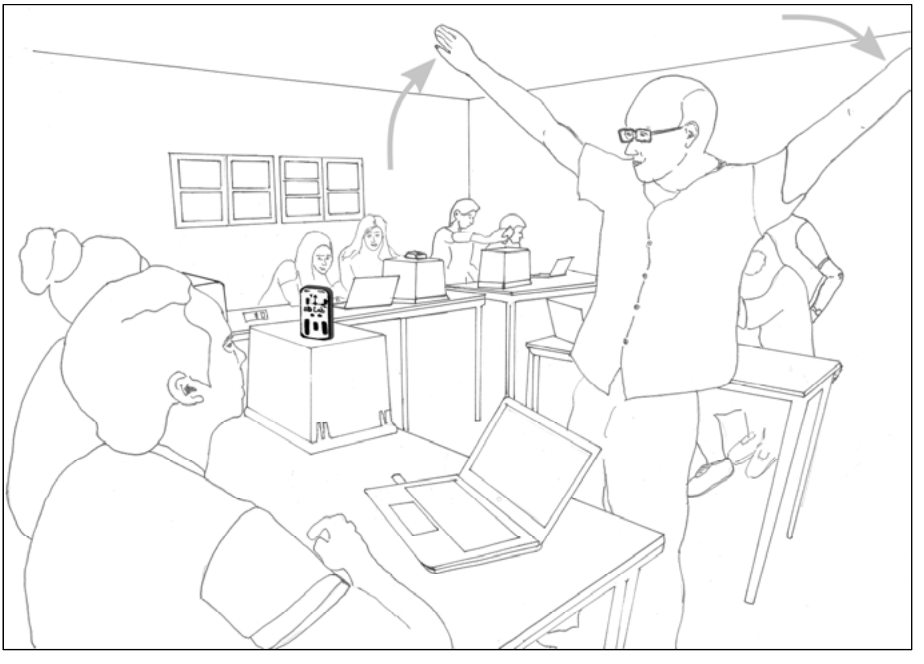


Figure 6.9. A facilitator recruits his own body by stretching out his arms in a right angle signifying a set of coordinate axes. He tilts his arms to demonstrate a repositioning of the orthogonal coordinate axes. (Paper II, p. 7)

Immediately after F2 departed from the group, our student pair started to devise a strategy to find the direction of the magnetic field. Essentially, they planned to make first one, and then two components zero. By spontaneously and eagerly reaching out for the sensor-box, while using words such as "*tilt*", "*move*", "*be zero*", the students were now fully utilising the pedagogical design of the iOLab system to "feel" their way to a solution.

Excerpt 3 – Extrapolating to a second component

Setting the sensor-box so that one component is zero is relatively simple; getting two components to show zero at the same time requires greater depth of awareness of what the readouts on the screen imply in relation to the positioning of the axes printed on the sensor-box and what that means for the magnetic field vector. It is at this juncture that the students started to truly reflect on the meaning of a negative component. At first they were confused:

S1: *Isn't that z? I don't understand, that should be z!*
[S1 moves the sensor-box towards him slightly, and looks at screen]
(While holding the sensor-box so that the x-component remains zero, S1 is now trying to make the z-component zero; the $+z$-axis in a line away from S1, y still up, x to his left)

S2: *That should be z*

S1: It's not moving! (referring to the green line on the screen)

S1 was clearly confused about why the z-component did not change by simply translating the sensor-box along a line implied by the printed-on axis, keeping the orientation fixed. This indicated to us that at this stage he was only coupling the numerical size and algebraic sign of the component value to his directional intuition (something should change by translating it). A silence ensued with S1 manipulating the sensor-box some more. The students then decided to try and make the y-component zero. Still holding the sensor-box with the x-value zero—and $+y$-axis pointing up—, S2 moved it from the top of the plastic box upwards in a straight line. See Figure 6.10 and note that the y-plot was negative and changed very little as she moved the sensor-box upwards.

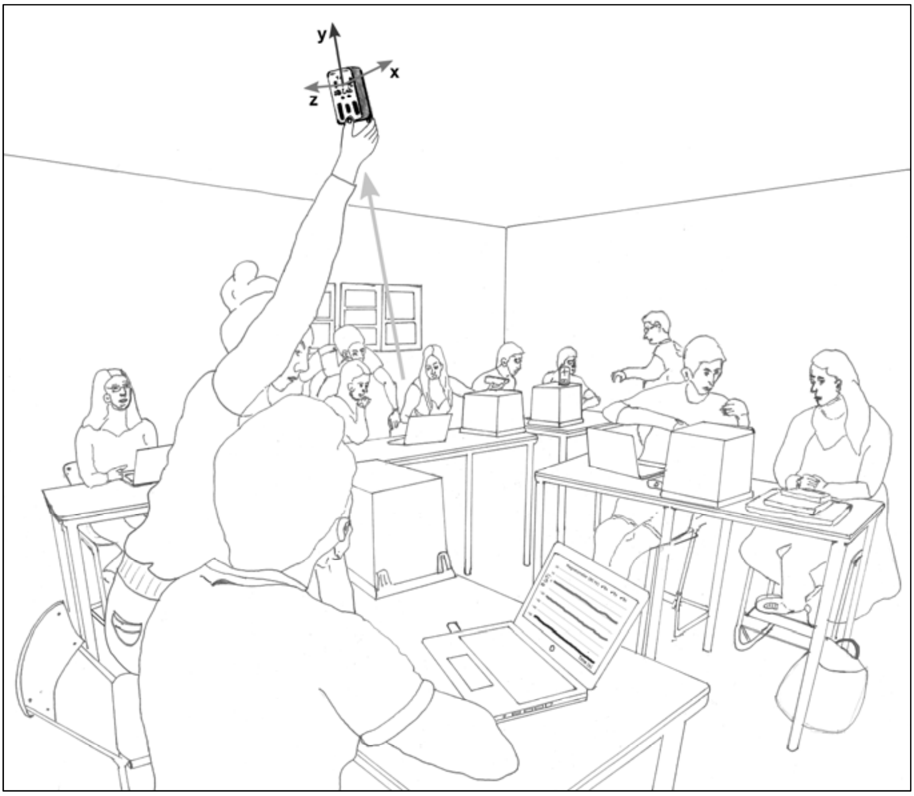


Figure 6.10. S2 gets off her chair and learns that up is not necessarily "more positive". (Paper II, p. 8)

Evidently, the students were trying to leverage their own intuition (or p-prims) that "*towards is closer to zero*" for the *z*-component and "*up is more*" for the *y*-component (see Paper I). This phase also vividly illustrates the significant challenges of working with 3D coordinate systems. Despite agreeing on a successful strategy of rotating the sensor-box to make one component zero, the students then struggled to successfully extrapolate this to a second component. With one component zero, keeping the orientation steady, they reverted to wanting to move the sensor-box upwards and downwards, forwards and backwards, or right and left. Now, once again, they appeared to consider the orientation of the axes to be fixed in the orientation shown in textbooks.

Excerpt 4 – Zeroing two components and fixing the arrow

A short while later, the students decided to call for assistance—F1 joined the pair. The students were guided in a Socratic fashion, which helped them resolve some of their confusions, especially as it pertained to the interrelatedness of the component values. The students were also led to reflect on what the component values meant for the description of the magnetic field (its direction). With some facilitator guidance, the students figured out that by rotating the sensor-box about an already-zeroed axis ("*tilted*") they could make a second component zero.

However, even when the students rotated the sensor-box in a way so that two components were zero, they still expressed some confusion about how this is possible. At this point the facilitator asked the students to fix the paper arrow in the direction of the one printed-on axis that was currently reading a non-zero value.

F1: *So if you… let's... fix this, let's… just… set this arrow; I'll give you some tape*

F1: *So this is your hypothesis*

[F1 points at red cut-out paper arrow now fixed to the side surface of the plastic box]

S1: *Yeah*

[S1 lets go of the sensor-box ("*measurement device*") on top of the plastic box and leans back (as if trying to "take-in" the full view/picture)]

F1: *So, if you now take this measurement device,…*

S1: *Yeah*

F1: *And try to see if this hypothesis, like, holds,…*

S1: *Yeah,…*

F1: *How would you point the measuring device if you want just the* ***x****-component* (letter emphasised) *to be non-zero, and all the others to be zero?*

All the meanings the students had made up to this point—figuring out the connections between the physics-specific resources, devising a strategy and productively implementing it after working out how moving the sensor-box ("*device*") would affect the component values—were now represented by the single red arrow, pointing towards the floor at a steep angle (see Figure 6.6); in the language of this thesis, the arrow was now a placeholder for all the meanings that had been made up to that point. With the arrow in this fixed position, F1 now based his probing questions on the notion of a static magnetic field (represented by the arrow) and a movable coordinate system which is manipulated with respect to this field. The discussion about the meaning of a zero value for a given component could now take place with the arrow serving as a "hub" for interaction.

F1: *Why is it zero?*

S2: *How come?*

F1: *Good question. Where is y pointing now?*

[F1 points at printed axes on the sensor-box and then pulls index finger in direction of +*y*]

S2: *Down…* (smiles; signifying that she is aware that this is not the case)

F1: *And how is it in relation to the field?*

[F1 points at and touches arrow]

S2: *Oh! It's, it's a ninety-degree angle then*

[While holding the sensor-box in one hand, she first pulls her other hand towards her (in +*y*-dir'n), and then makes a right angle and draws her fingers over the arrow]

F1: *Yes*

S2: *Ah-hah, that is so cool! Ahh, Wow!*

[Broad smile directed at F1]

S1: *Yeah, that makes sense*

[S1 taps on table just before and after talking]

S2: *Yeeesss!*

What is striking here is S2's almost immediate and spontaneous response to F1's direct question about the spatial relationship between the *y*-axis and the cut-out arrow ("*the field*"). The student suddenly realised that a particular component value is related to the angle (in this case 90°) between the respective reference axis (+*y*) and the "static" physics quantity (the magnetic field). Importantly, S2's synchronised gestures—hand drawn along *y*-axis, then making a right angle immediately followed by tracing the arrow, and talk, "*…it's a ninety-degree angle then*", signified that the student was personally taking on this meaning. This was confirmed by both students' verbal appreciation and expression of joy at finally grasping the idea, the "*Ah-hah*" moment captured in the transcript. Later (as depicted in Figure 6.11) the moment was captured when S2 simultaneously introduced her thumb aligned opposite to the red arrow, and curled her fingers around her thumb in a sweeping gesture, in conjunction with her explanations of the algebraic signs of the component plots on the screen. After the "*Ah-hah*" moment, the students quickly started to check their own understandings by reorienting the iOLab in a number of ways and explaining the resultant readouts.

By this time most of the groups were starting to fix their arrows. (see Figure 6.6). With this "picture" of the magnetic field in the room, the students also learned something else about the Earth's magnetic field; that it is approximately invariant in the classroom, and that the direction has a steep dip into the ground.

Excerpt 5 - Students now test and cement their newly acquired understandings

F1 continued in a series of probing questions and follow-up discussions about how the manipulation of the sensor-box was related to the graphical readout in reference to the cut-out arrow. While holding the sensor-box in position near the arrow, with gaze checking the computer values, they were able to predict and explain the reasons for certain components being zero and the negativity (or not) of the non-zero component (see Figure 6.7).

F1: *So now, if you want to* ***align*** (emphasis) *this vector to this vector, what should you do?*

[F1 points in order at printed-on axes in direction of +*z*, then at red arrow]

S2: *Ah-hah! This way ... ah, OK,*

[S2 grabs the sensor-box (smiles broadly) and holds it with +*z* pointing directly opposite to the arrow]

F1: *Yaahh…*

[F1 looks at S1 (to check if he also gets it)]

S2: *Yeah, ah-hah, ... it's a negative, ... because it's pointing this way and...*

[S2 looks at screen and explains negative value with hand and finger first gesturing along direction of arrow (down at an angle), then draws index finger in opposite direction]

S1: *Yeah*

[S1 nods head up and down]

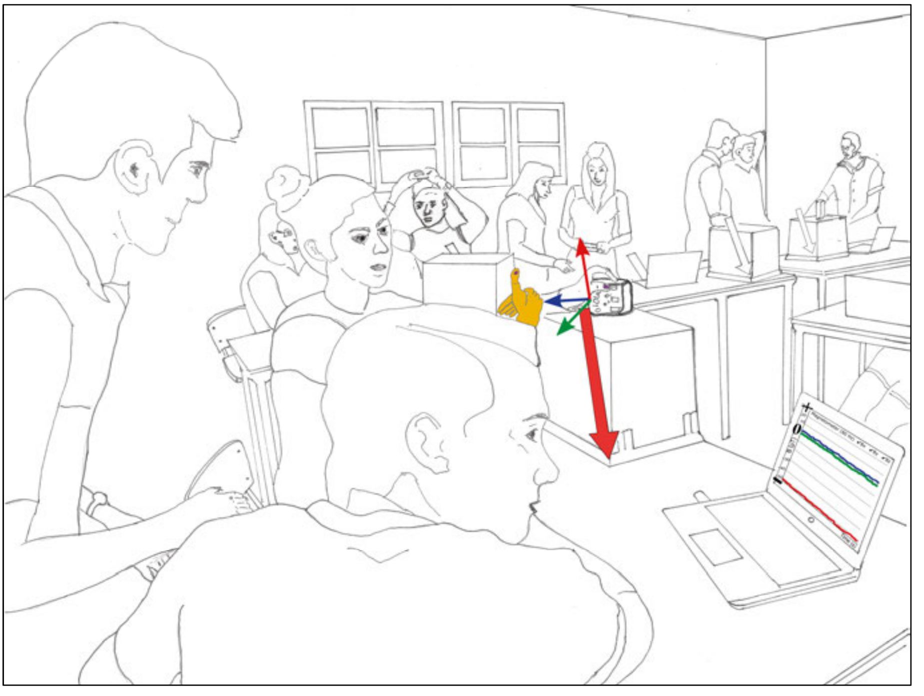


Figure 6.11. S2 holds the sensor-box in position with her left hand, so that the x-axis printed on the sensor-box is anti-parallel to the arrow, with the *yz*-plane perpendicular to the arrow. Firstly, she curls her fingers while looking at the screen, and says, "they are all zero"—referring to the zero *y* and *z* plots. Secondly, her thumb aligned opposite to the arrow accounts for the negative *x* plot—which she confirms with speech shortly after in discussion with the facilitator. (Paper II, p. 11)

In Figure 6.11, S2 used talk and gestures—curling her fingers in the plane perpendicular to the *x*-axis, and pointing her thumb in the opposite direction to the arrow—, to show and explain respectively, why the *y* and *z* plots were both zero, and the *x* value was negative. F1 followed this up by asking the students to set the sensor-box in new positions—for example, "*What if you flipped it around?*" which the students duly answered correctly. He then concluded his interaction with them by summarising what they had learned about coordinate systems.

Both the instances of the student introducing a hand gesture—Figures 6.7 and 6.11—to explain negative and zero components (with reference to the persistent resource, the arrow, and the position of the iOLab sensor box) were taken as signs of learning about the movability of coordinate systems. Different to the usual unconscious gesturing that accompany speech, these hand gestures were deliberate introductions of a resource that connected the meaning deposited into the red arrow (the direction of the field) to the meanings they had now grasped from correctly interpreting the component values on the screen. Furthermore, the students, in their articulation of their understandings in answering the questions from the skilled facilitator who purposefully introduced variation (“what if you flip it around”, “etc.), evidenced an appreciation of the disciplinary relevant aspects of the Cartesian coordinate system—its movability and the meanings of the algebraic signs of the components—in finding of the direction of the Earth’s magnetic field using a movable 3D magnetometer sensor.

6.2.4. Discussion

The experience of the participants in Case Study (A) supports the assertion that introductory-level university students may initially view Cartesian coordinate systems as being fixed in standard orientations. To address this transient learning challenge (Fredlund, Linder, et al., 2015), students were provided with an opportunity to notice the movability of coordinate systems. Following the variation approach described for physics-related contexts (as examples, see Fraser & Linder, 2009; and Fredlund, Airey, et al., 2015), in order for students to notice any disciplinary aspect, this needs to be varied whilst other disciplinary aspects remain constant (see Section 3.4.5). To achieve this goal, a relatively static, unknown quantity was chosen for the students to explore (the Earth’s magnetic field) with a movable measurement tool (the iOLab sensor-box and system).

The learning activity was set up in such a way that the students would experience the variation in the orientation of a Cartesian coordinate system against a background of the invariant direction of the Earth’s magnetic field. This was achieved in three ways. Firstly, by having a tool that provided the students with a “visible” coordinate system; secondly, by having the students fix a paper arrow to denote their measured direction; and thirdly, by the students seeing the same result being arrived at by their peers—a spread of arrows fixed in the same orientation distributed throughout the classroom (see Figure 6.6)..

In most laboratory exercises, determining the magnitude and direction of an unknown quantity would signal the end of the laboratory task. However, in this case, the learning goals were focused on students learning about the movability of coordinate systems. The arrow now served as a persistent, visual representation (Fredlund et al., 2012; Paper III, p. 24; Paper V, p. 102) of the constant background signal against which the movability of the coordinate system could be experienced.

Up until this stage the students’ attention had been focussed on finding the direction of the magnetic field by manipulating the sensor-box. Now, with this direction determined, students could turn their attention to the iOLab system (the sensor-box and the information on the computer screen) itself. In essence, students were encouraged to make sense of the process they had just gone through to fix the arrow in terms of the manipulation of a coordinate system. Here, the printed set of axes on the sensor-box became important. Students could now manipulate the sensor-box (and by extension, the coordinate system) into different orientations with respect to the arrow and check the outcomes on the computer screen. At this stage, the facilitator could probe the students' understandings of the meanings of the Cartesian components by asking the students to predict the necessary orientations of the coordinate system that would achieve particular outcomes in the readouts of the three components on the screen. Furthermore, the students experienced movability without having to engage in numerical calculations. This aspect allowed the students to engage with the task in a pronounced conceptual way (see Hewitt, 1983, for a discussion on learning physics conceptually).

The limited dataset presented in this case study does not allow for generalisation of results. However, what it does do is provide a rich description of how an educational experience can provide students with a new and meaningful learning experience through a fine-grained analytical description. In other words, while it cannot be claimed that all (or even a majority) of physics students initially conceptualised coordinate systems as being fixed in standardized orientation, an illustrative example of students who did view coordinate systems in this way has been provided. At the same time, how this learning challenge may be effectively tackled has been demonstrated.

Papers I and II have shown that some introductory physics students do indeed think about using Cartesian coordinate systems as though they are essentially "locked" in one orientation. One way in which this learning challenge can be effectively addressed is by getting students to engage, as in Case Study (A), with a movable measurement device (iOLab) in a constant field (the Earth's magnetic field). Based on this study, it is proposed that physics lecturers explicitly address the movability of coordinate systems in the kind of way that has been exemplified by the conceptually-oriented task designed around a probeware tool (such as the iOLab) in an open-ended physics laboratory environment that encourages interactive engagement.

6.3. A potential barrier to learning physics concepts – the overvaluing of mathematical resources[38]

For Case Study (B) (submitted as paper IV), the initial research interest was to conduct in South Africa a parallel study to Case Study (A). Could similar results, as described in the preceding sections (6.1 and 6.2), be obtained when first year South African university students of a similar age (17-19 years) and educational experience as the Swedish gymnasiet students were asked to solve the identical task using the same laboratory equipment and setup?

[38] Paper IV

There were many sequences in the South African data set that confirmed the findings of Case Study (A) (see previous sections and Papers I–III). However, there was one major difference in the way that the South African students approached the task. The role of this section is to describe and explain this difference.

6.3.1. Competence in using mathematics in physics

Previous research has shown that students tend to overvalue mathematical calculation (see the introduction to Paper IV). The iOLab magnetometer task designed for Case Study (A) was purposed to create opportunities for students to appreciate movability, without the need to resort to mathematical calculation. This is important, since it was reasoned that grasping a conceptual understanding of a mathematical resource in this way would benefit students when they are later asked to use the resource to solve physics problems.

However, it is possible to solve the magnetic field direction task by simply setting the iOLab on a stable surface, writing down the component values, and calculating using the Cartesian coordinate system equations. Note however, that the mathematical competence to solve the task is predicated on an understanding of what the three Cartesian components mean in relation to the magnetic field, itself an invented physics concept to express the physics community's knowledge about magnetic phenomena in nature. Mathematically, solving for the direction of the magnetic field vector is effectively a coordinate transformation—from Cartesian to polar coordinates. Once this is done, to visualise the field vector (the task was for students to paste a red arrow in the room), the polar coordinates (the angles relative to the Cartesian reference axes) must be interpreted in relation to the physical position of the iOLab sensor-box (here, the printed-on axes are critical). Only then can the student reconstruct the direction of the magnetic field vector from its components, which is the stated goal of this task. For an expert, who possesses the required mathematical conceptual understanding within the physics context, this may seem like a relatively simple calculation, but in terms of the conceptual (theoretical) framework adopted for this thesis, behind the mathematical calculations lie the ability to fluently work with the mathematical resources and link these to the physics phenomena and the other resources made available in the task (such as the graph plots, the red arrow, the printed set of axes on the iOLab sensor-box, etc.). This is a key notion that is leveraged in Section 6.4, in which social semiotics is used to define representational competence in and across semiotic resource systems. I will show that even for basic physics topics this is more complex than many physics educators may at first think.

6.3.2. Summary of analysis for Case Study (B)

The learning activity, classroom setup, and protocol for conducting the research in Case Study (B) was nearly identical to the first case study. The one difference being the number of students who participated in each of the sessions. Each of the first two sessions accommodated three pairs of students, and the final session had only one pair. In all three sessions there was one facilitator (the author of this thesis) present.-

As before, the first step of the analysis saw the researcher making notes of the students' interactions as they worked their way through the activity. However, unlike in Case Study (A) where the analysis focussed exclusively on one pair of students, here excerpts were drawn from across the seven pairs. The reasons for adopting this strategy is explained below.

What emerged immediately from the three activities was the fact that six of the pairs of students, after briefly moving the iOLab around, were not interested in manipulating the device; rather, they simply placed the device where they found it and stared at the computer screen for long periods of time.

This is in stark contrast to the actions of the Swedish students in Case Study (A). Barely a minute after reading the instructions, the Swedish students started moving the iOLab device around, expressed excitement at the changes they observed on the graphical display, and started making the connections that were needed to solve the task. It was therefore somewhat surprising, that none of the South African students, with the exception of one group seemed to adopt this approach, despite the protocol and resources being identical to that for Case Study (A).

There was one additional teaching aid that was available in both settings. In Sweden, the researchers had brought a large wooden model of a set of orthogonal Cartesian axes (visible in the left-hand side of figure 6.12). In South Africa a scaled down version of this model was made by inserting coloured party straws into holes drilled into a dice (see right-hand side of Figure 6.12).

The 3D cartesian axes has a high pedagogical affordance and is therefore good for explaining physics. The pedagogical affordance of the South African model was further enhanced by having the colours of the straws match the colours of the plotted lines of the graphical display on the computer screen. However, the model has a very low disciplinary affordance, and is therefore not really useful for doing physics.

Of further interest is the fact that whereas the large wooden model was not used in Case Study (A), the dice-straw came to play an important role in Case Study (B) as will be discussed below

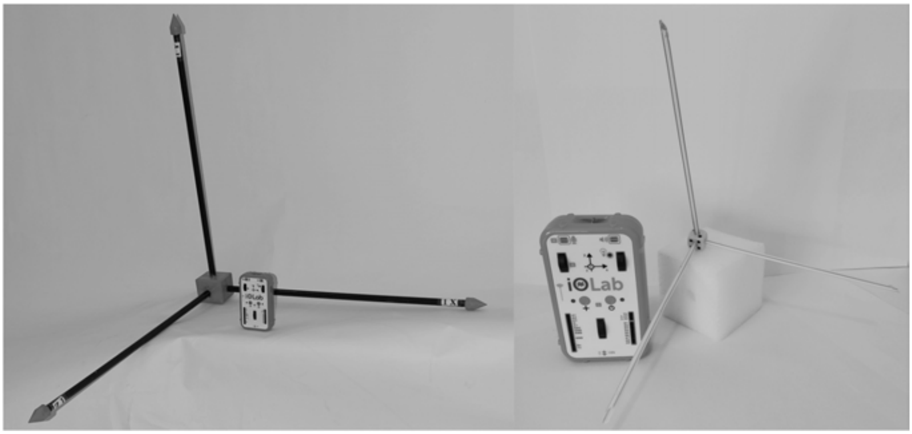


Figure 6.12. The two 3D Cartesian axes models made available. The large-scale wooden model made available in case study A is on the left, and the dice-straw model used in case study B is on the right.

The transcript extracts which follow represent the approaches of most of the student pairs in this case study. Note that individual students featuring in the extracts are simply labelled S3, S4, etc., as a continuation of the labelling scheme used for Case Study (A). Since the extracts which follow are from different groups in different activities, they are not presented in strict chronological order but rather illustrate the kinds of meaning-making that occurred across the student groups.

Towards the start of the learning sequences, most of the students seemed to spend a considerable time just peering at the screen and scribbling in their notebooks..

Extract 1

F3: […finishes introducing the iOLab and the activity; some time passes]

S3: … (no speech)
[S3 picks up the iOLab, looks at the screen, and replaces it in the same position]

S4: … (no speech)
[S4 picks up the red arrow and places it back on the table]

The pair (S3 and S4) then had the following brief encounter with the facilitator, who initiated the interaction after noticing the low level of interaction in this group (no talking and manipulation of the device).

Extract 2

F3: *So guys, what is happening?*

S3: *Should the lines just be flat?*
[S3 is looking intently at the screen]

F3: *What do you think these three lines represent?*
[F3 leaning over and pointing at the screen]

S3: *I have no idea*
[S3, without looking up, still peering at screen intently]

S4: (no speech)
[S4 looking at screen, then scribbling information on the provided A4 page]

During the time that the facilitator was resolving some problems with the iOLab devices, the students began to talk more freely amongst themselves, and the researcher was able to gain some insights into what the students had been thinking when they had been sitting quietly. The following interaction took place almost 20 minutes after the facilitator had introduced the task.

Extract 3

S3: *So somehow, we have to figure out how to get these three*
{S3 takes hold of the dice-straw model and holds it in front of him in one hand, and points index finger of other hand over straw model}

S4: *The arrow, are we actually supposed to move this?*
{F4 picks up the red arrow and waves it in front of his group partner}

S3: *I don't know man ...*
[shakes his head looking at the arrow]

S3: *If we had two components, I know how to connect…*

S3: *How do you…*
[S3 now looks up and across towards the other groups]

S3: *Guys, how do you combine 3 different components into one?*

S5: *…Why do you* ***want*** *(emphasis) to combine…*

S6: *…****Vectors*** (emphasis), *how the heck!?Vectors.*
[expression of amazement on her face (as if to say, "you should know this")]

S3: *Yah, vectors. Vectors, we only had two components* (referring to an earlier class work exercise where they only added two components)

S6: *Can't you add* (indistinct)*… three, you'll add them all, head-to-*(tail)...

F3: …(interrupts groups briefly to check the functioning of the iOLabs)

S3: (S6), *you said vectors. How?* W*e only had 2D vectors, that you combined, x and y. Now you have a third one. How are you going to add a third one?*

S6: *I did maths. I did vectors in my Swokowksi book* (referring to a common first year mathematics textbook used in South Africa)

S3: *I don't know what that means*
[S3 shakes his head side to side in an exaggerated way]

S6: *I did extra work, and I had to add it in 3D*
[S6 smiles]

S3: *Explain*

S6: *It's like, you must draw the Cartesian plane in 3D. And you draw the points, and then you move them head-to-tail on a 3D plane*

S3: *Adding vectors head-to-tail, makes sense*

[S3 takes hold of and closely inspects the dice-straw model]

..//.. S3 and S4 now return to their own pair group discussion/

At first the students appear to be struggling to make sense of the range of resources in front of them—the arrow, the model set of axes, and the graph output on the computer screen (although their interaction with the 3D Cartesian dice-straw model does indicate that they were interested in the Cartesian component values on the screen) Significantly, unlike their Swedish counterparts in Case Study (A), they made no link to the printed axes on the iOLab sensor-box. In fact, most of the student pairs hardly ever manipulated the device, despite the facilitator demonstrating how the device could be rotated.

Once they began engaging across the groups, what was evident is the explicit appeal to mathematical knowledge made by one of the students (S6) who went on to explain quite confidently to the other students how to perform the calculation. However, the video data showed that even this student and partner struggled to successfully implement the intended strategy of adding vectors in 3D.

After another period of staring at the screen and performing adjustments via the touchpad and keyboard of their computer, two of the students (S3 and S4) had the following discussion, which illustrates the focus the whole class had on determining the direction of the magnetic field by mathematical calculation. They referred explicitly to a previous physics problem solving activity (relative motion) in which they employed mathematics to add vectors in 2D.

Extract 4

S3: *Because we need to find,… it's like, you know what we do with when we have the 2-D motion, the boat,*

S4: *Mmm*

S3: *We have to work out the speed and direction at the end…*

S4: *The final…*

S3: *When they give you, you first break it up, and then you get the two different speeds and the two different directions. Then you add it together, then you get the direction.*

S4: *Yah, but we used, we did that using Pythagoras*

S3: *Mm, but nowhere, the issue here now is, we also have to find the magnitude and direction, but now we have these* (three) *different components, and that is the issue*

S4: *But can't we find the magnitude using these values here*

[S4 points to screen]

S3: *What* (*name* of S6) *said now, head-to-tail, sounds ok, but Ahh!* (exasperated)

[S3 again looks at screen and fiddles with touchpad]

In the period that the facilitator was sorting out the problem with the iOLabs, students moved around and for a brief period (a couple of minutes) worked in groups of three. S4 joined S7 and S8 after which S7 proceeded to explain the strategy of their group to S4. S7 started with drawing a head-to-tail vector addition diagram on the A4 page (the top-right of Figure 6.13).

Extract 5

S4: *We were discussing about the boat; that was just 2D, so we were like, what if we use the same strategy as we did with the boat*

S7: *You can …* (some indistinct speech) *... how can I say now, when you come to that point where you must combine all…*

S4: *Then you must use Pythagoras, isn't it?*

S7: *Pythagoras, look, Pythagoras has two sides…*

S8: *Two, x and y…*

S7: *Two dimensions to find the magnitude of the third one*

[S7 uses two fingers of his left hand and index finger of right hand connecting the other two fingers to indicate the head-to-tail vector addition]

S8: *Look,…it's a triangle…*

S4: *…the third one*

S7: *But, but, just give me that pen…*

S7: *You can add mos* (slang Afrikaans word suggesting something that can be done with a little effort) *many vectors*

[draws head-to-tail diagram on A4 page—see Figure 6.13—and continues tracing his pen over diagram as he explains further below]

S7: *We have a direction here, nuh, ...*

S8: *Uhh…*

S7: *…We have a direction here,*

[S7 continues drawing]

S8: *And, then we're going to take (indistinct), and add it...*

S7: *That's more than two vectors…*

S4: *And, the resultant?*

S7: *Ek wietie* (Afrikaans for *I don't know*). *Oooo, I don't know, in terms of angle-wise! Sien jy* (Afrikaans for "*do you see"*)?

S8: *Ohhh, I get you…* (expressing worry at the magnitude of the task) *so this is going to be, y?*

S4: *Why don't you do it, break it down into two*

S8: *....And two each*

S7: *…this is what we discussed …*

S7: *So y-x, and then y and z, and then x and z.*

[pointing at the three diagrams]

S4: *So, how will you combine them in the end?*

S7: *But, we will get angles relative to each other…*

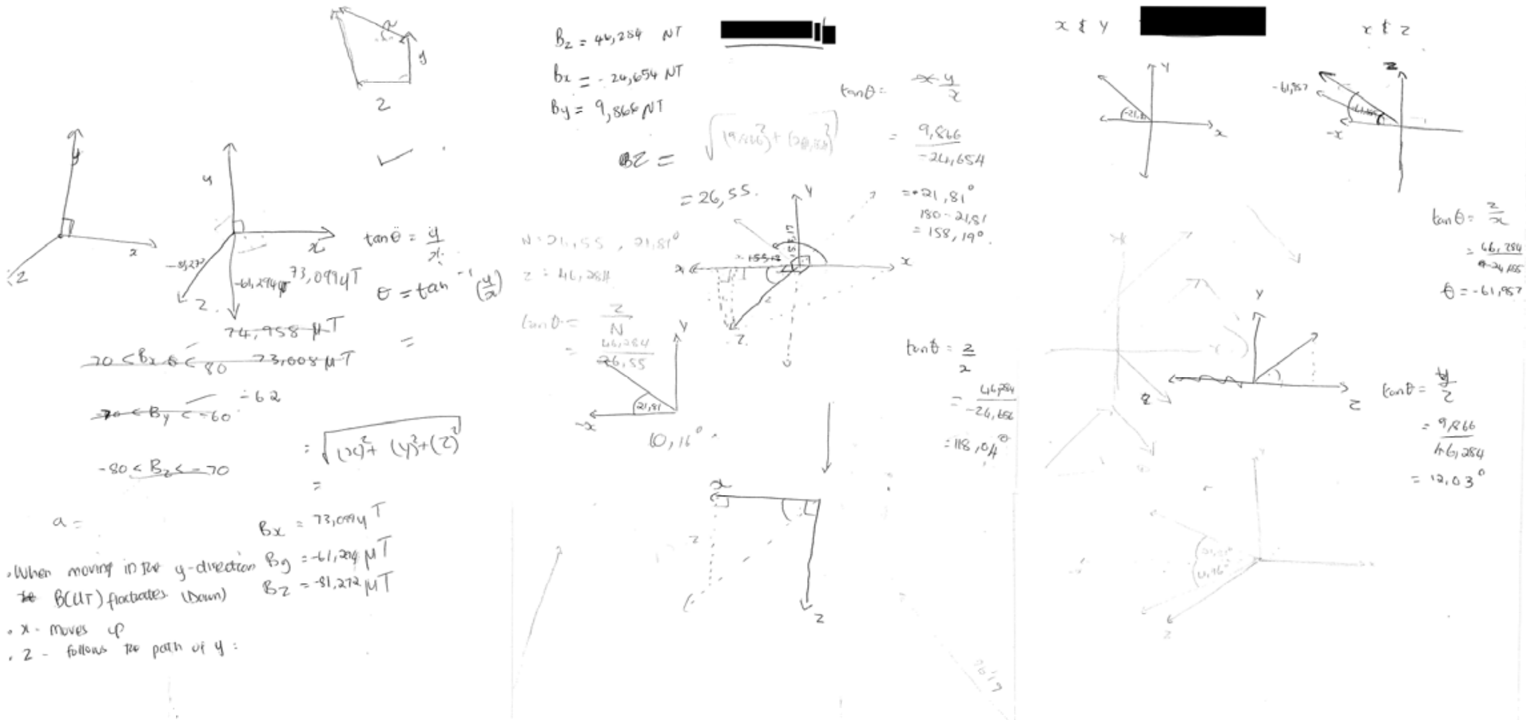


Figure 6.13. Scans of one pair's calculation work. Notice the 3 two-component angle calculations. The student's names are redacted (black areas on the figure).

S7 then proceeded to explain his calculations of the angles for each of the three two-component trigonometric calculations. He picked up the arrow and quite ably explained the angles with reference to an imagined set of coordinate axes he has visualised to be aligned to the way he was sitting at the table—the arrow was held at the calculated angles relative to the three pairs of axes. At the end of this interlude the following occurred.

Extract 6

S7: *In between **all*** (emphasis) *of them* (laughs now mockingly at himself) [shaking his head in rapid fashion side to side and looking at S4]

Interestingly, S7 used the red arrow as a visual representation of the resultants of his two-component calculations (see Figure 6.13, which are scans of the groups actual working). Unfortunately, while they were successful in calculating two-component directions (with S7 even being able to visualise the projections of the resultant vectors onto two axes at a time), they were not able to solve for the direction of the magnetic field.

This pattern of attempting to solve for the direction of the magnetic field using mathematical means repeated itself with the three pairs of students in the second session. Based on his experience with the students in the first session, the facilitator at first allowed the students to proceed with their attempts to solve the task mathematically. The value of this approach paid dividends with at least two of the three student pairs—after they had been bogged down in the calculations, they came to appreciate the movability of coordinate systems even more (these two pairs had discussions with the facilitator; it does not mean the other pairs had not come to the same appreciation. Preceding the interaction between the two students, S9 and S10, with the facilitator recorded in the excerpt below, the facilitator guided this student pair in a Socratic dialogue style to connect their calculations, through mediation of the dice-straw model, to the task goal, the determining of the magnetic field direction and the fixing of the red arrow. In the terms used in this thesis, the facilitator was performing 'static' transductions for the students with the aid of the dice-straw model. Since the iOLab was not moved, the graph plots became persistent representations in the engagement with the students—the algebraic values on the screen were connected to the dice-straw model's three axes, which in turn were aligned with the printed-on axes of the iOLab. Because of this, the facilitator had to guide the students to appreciate the movability of the coordinate system by instructing them to manipulate the device. After fixing the arrow, the student pair were told, just prior to the recorded interlude below, that they should manipulate the device so that only one component plot is non-zero.

Extract 7

F3: *Oohh, look at that, now you've got both x and z to be zero*

S9: *z is zero, x is not so*

F3: *But it's close to it, right*

//…a short while later

S9: (no speech)

[S9 rotates the iOLab about the *x*-axis, with *x*-componeent being zero, and ends with the *y*-axis along the magnetic field]

F3: *Ah-hah, you see, you rotated it now about the x-axis, ...*

{S9 is holding the iOLab so that the *y*-axis is more or less aligned with the magnetic field in the room (steep negative inclination, out of the ground},

[F3 inserts his hand in the space between the students and makes a rocking motion forward with his palm over the iOLab to signify what S9 just did in rotating about the *x*-axis]

F3: …, *and then you got z to be zero, do you see that?*

[F3 points at the screen, then resets his palm aligned with the long face of the iOLab, which is also the *y*-axis, and the magnetic field]

F3 *You had x zero, x is that way, you didn't change x, ...*

[F3 draws finger left and right in the *x*-direction, then lifts arm and points into the distance to the right to signify "that way" in the +x-dir'n]

F3: *But, but, twisting it around x, you now made z zero, ...*

[F3 now in an exaggeratedly slow motion again rocks palm around the line of *x*, then points at the *z* on the iOLab's printed-on axes]

F3: …, a*nd now you only have y*

[F3 points arm and hand in the direction of *y*]

F3: *So, in which direction is your field pointing? Which, look,…*

[F3 looks at S10 and at iOLab, wanting her to attend to the printed-on axes).

S10: (Gasping sound)

[S10 now also points her finger along the direction of the *y*-axis, but moves her gaze from the iOLab to the arrow pasted on the cardboard box,]

F3 *...along, ..., y*

[S10 makes a body gesture expressing disappointment – hangs head to side, upper body slightly leaned back; F3 looks at S10]

F3: *Which means, you've got to, …, align your box like this*

[F3 walks around to the box, and moves it around; in the meantime S9 comes to the same realisation, smiles and points his fingers in the *y*-direction up and down]

S10: *I'm actually shocked how we overlooked this!*

[S10 musing at herself and her partner]

//…a short while later…

S9: *So we figured out, our R* (referring to the resultant, the magnetic field vector), *is pointing in that direction*.

[Points arm and hand at an up-angle in the direction of the determined field vector]

S9: *What we didn't understand, the mistake that we made* (slightly subdued voice)*, ..., we didn't know that this is also a compass, why it was difficult*

S9: *So what we did, we tried to make x and y, no z*

S10: ...I should have known that all along!

[S10 leans forward and gasps]

S9: *If we knew this was a compass* (smiling broadly)!

Both the realisation by S10 (gasping sound, alignment of finger with *y*-axis while shifting gaze from the printed axes to the arrow) and the comments by S9 that he didn't realise before he could use the iOLab as a (3D) compass, was evidence of the students having finally appreciated the movability of the coordinate system. After first performing copious calculations—this pair actually obtained a reasonable mathematical answer, but referenced their result to the dice-straw model that was not aligned to the iOLab's printed-on axes—they were now able to make the connection between the iOLab axes held in their hands and the arrow which stood for the direction of the magnetic field.

The single pair that took part in the third session were more advanced—they had completed two half courses in first-year physics, stretched over two years (see the discussion around ECP courses in SA in the Preface)—, whereas the other six pairs had completed only the first ECP half course. The two students seemed to grasp quite quickly the connection between the components and the graph values. At the start they did not consider the iOLab position. However, once they began moving the device around, they quickly realised that the printed-on axes played a role. They then aligned the iOLab axes with the straws on the model, indicating that they now understood that the measurements were in relation to the orientation of the device but also showed how they assumed that coordinate systems are fixed in an up-down orientation. They had aligned their device with the visual coordinate system as though this was a fixed reference. This group was eventually able to reconstruct the direction of the Earth's magnetic field by pointing the red arrow first along the highest value component (*z* in this case, the green straw and iOLab *z*-axis pointing up), and successively adding in the other two components by tilting the red arrow towards first the one axis, and then the other. The red arrow now pointed away from them at an up-angle—as noted previously, the magnetic field in South Africa points steeply out of the ground. However, they did not appear confident of their result and called the facilitator over to confirm that they had correctly identified the direction of the magnetic field. The facilitator helped them fix the arrow (by pasting it onto a cardboard box), and then asked them if there was another way to confirm their solution—the direction was approximated by their 'visual' version of performing the head-to-tail addition of the three components using the dice-straw model as a persistent representation. It was clear that the students had not yet appreciated the movability of the device, and hence the facilitator wanted to check whether they had appreciated the movability of the coordinate system. By guiding them in a Socratic style, similar to the way that the facilitator in Case Study (A) had done, the facilitator asked them to predict and explain the values (0, +, −) of the components for different positions relative to the found direction (red arrow now pasted on a large cardboard box). The students made a few mistakes along the way but were eventually able to connect it all together. The dice-straw model seemed to offer a key affordance for these students, as illustrated towards the end of the extract below:

Extract 8

F3: *Now that you have the z-axis aligned to the arrow,…ok…*

[F3 points at the printed-on axes on the iOLab sensor-box, being held in the air by S11 with both his hands, so that the printed-on *z*-axis is aligned with the red arrow pasted onto the provided cardboard box]

F3: *..., does it really matter, in which direction x and y point?*

[F3 pointing at the printed-axes again, first at *x*, then at *y*]

S11: *Well, if I,… change the,… , if I rotate it,…, like this,…*

{S11 rotating the iOLab anti-clockwise about the *z*-axis very slowly, while gazing at screen}

S11: *,…it does seem to move, the x and the y*

F3: *How much, does it move a lot?*

[F3 walks around behind the students to look at the screen, so is referring to the small variation observed on the *x*- and -plots on the screen]

S11: *No, gradually,… towards negative*

{S11 rotating but not exactly about the *z*-axis}

S12: *…Yah*

S11: *And if we go this way*

{S11 rotates sensor-box anti-clockwise about *z*-axis}

F3: *So, what kind of movement are you doing, how are you moving it?*

S11: *Rotation, ...*

S12: *Rotating*

[Both S11 and S12 watching the screen intently]{S11 still rotating the device about the *z*-axis approximately

S11: *,…rotating it, around the* ***z***-(emphasis) *axis*

F3: *So, your z-direction points where?*

S11: *Uhhh,… , in the direction of the red arrow?*

[Both S11 and S12 immediately, and at the same time look at the red arrow in front of them, which is pasted on the cardboard box; S11 also looks by moving his head towards the red arrow (his hands are both holding the iOLab in place, so he is using his head to point)]

F3: *Yah, but show me*

S11: *That way*

[S11 now looks at the iOLab in his hands, and lifts his left hand and points his finger along the line of the *z*-axis]

F3: *That way, OK, ..., and then your x-component points in which direction?*

S11: *That way*

[{S11 now while holding the iOLab}, points his right index finger along the printed x-axis]

F3: *And y, ... that way, ...,*

S11: *… y as well, ...*

[S11 points index finger of left hand along printed *y*-axis, whilst still pointing right index finger along *x*]

S12: *…, y is that way*

[S12 confirms by also using his hand and index finger to draw a line in the direction of *y*]

F3: *So, how do you describe, if you were to just show me, instead of just using words, right, how would you explain the directions relative to each other?*

{S11, all the while is holding the iOLab in place with his index fingers aligned to the *x* and *y* axes}

S11: *They are perpendicular to ...*

[S11 & S12 alternately looking at the iOLab and the screen]

F3: *They are perpendicular. So how do you see perpendicular in space?*

S12: *Space...*

[S11, now almost immediately looks at the dice-straw model as the word “space” is uttered, and {picks it up}]

F3: *Ah-hah*

{S11 now aligns the dice-straw model over the printed-on axes of the iOLab which is still being held in position with his other hand}

F3: *Aha*

[S11 & S12 both chuckle in a way that indicated they now get it]

[S11 rubs hands in gleeful manner]

The facilitator and the students then had a discussion about the Earth’s magnetic field in their current location. The students were asked to calculate the angle of inclination—the dip angle of the Earth’s magnetic field, which would be negative in South Africa. S12 immediately had an idea and stated that they should make one component zero; this was taken as further confirmation that the students now understood the movability of the coordinate system.

Only the single pair of students in session 3 were able to determine the direction of the magnetic field in the room from their mathematical workings; all of the other students failed in their attempts to do the same. This suggests that the students overvalued the mathematical resources and did not realise how to simplify the task through movement. They just kept their iOLab and thus the coordinate system fixed. And the arrow, which played such an important role as a placeholder for previous meanings for the students in Case Study (A), was not utilised in a similar way here. Instead, the teaching aid (the dice-straw model) with its high pedagogical affordance, provided the bridge between the component information provided on the computer screen, the printed-on axes on the iOLab device and the arrow. It was only after making these connections that students were able to appreciate what the coordinate system's role was in finding the direction of the magnetic field. However, the evidence here also suggests that the availability of the dice-straw model may have created a barrier to appreciating the affordances of the iOLab system in grasping the movability of the coordinate system.

In both case studies the students tended to view co-ordinate systems as fixed in standard orientations. In Case Study (A), the printed-on axes of the iOLab sensor-box, and in Case Study (B), the dice-straw model and not the printed-on axes of the iOLab sensor-box. This would suggest that even if a tool has high pedagogical affordances associated with the learning task, there is a potential for it to interfere with the intended learning path. This is to be expected since pedagogical affordances are for the most part individual rather than collective.

6.4. Representational competence[39]

Section 3.3.1 included a brief overview of the use and application of the notion of *representational competence* in both science education and physics education research (see also the brief overview given in Section 2.5.2). In Paper V, a social semiotic lens is used to propose a new characterisation (or definition as it will be referred to here) of representational competence for application in PER.

Whereas I would argue the definition is general enough to be applied to most scientific work, as noted in the literature review, the different scientific disciplines view the role of representations quite differently and therefore have developed their own nuanced definitions of representational competence. The definition adopted here builds on those developed by A. Linder et al. (2014) and De Cock (2012).

[39] Paper V

What follows is an unpacking of this definition in ways which will allow us to operationalise the development of representational competence from a social semiotic perspective.

6.4.1. A new definition of representational competence in physics

Representational competence for physics is defined for the purposes of this thesis as follows:

Representational competence (R) is the ability to appropriately interpret and produce a set of disciplinary-accepted representations of real-world phenomena and link these to formalised physics (scientific) concepts.

This definition was developed precisely because many areas of science are based on creating scientific explanations of real-world observations. In physics this is arguably even more critical, as most phenomena can only be experienced through mediation in a semiotic sense—for representations, or semiotic resource systems, are the only means through which disciplinary knowledge about physics phenomena may be communicated (see Sections 6.1.1. and 6.1.2). It therefore stands to reason that students should be exposed to investigating disciplinary-specific representations and should be afforded opportunities to discern their relation, on the one hand, to observation and on the other to disciplinary concepts.

The definition can be visualised in the form of a triangle (see Figure 6.14).

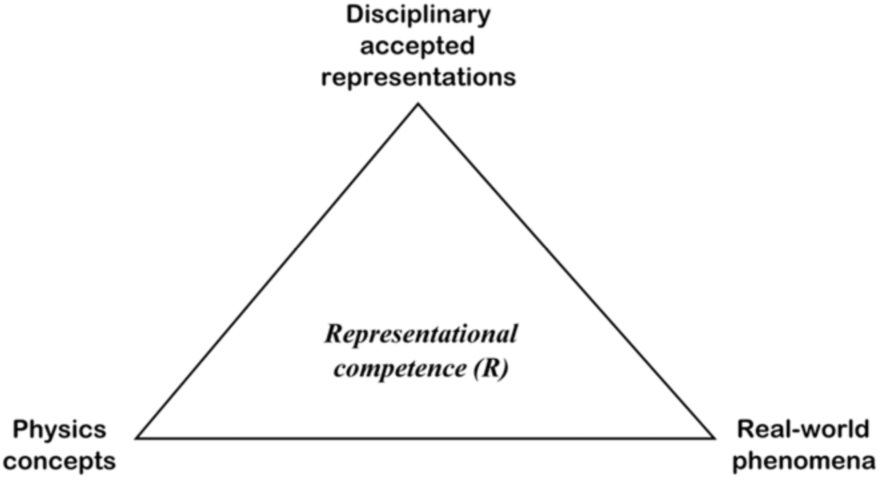


Figure 6.14. Representational competence (R) consists of modelling real world phenomena by linking disciplinary-accepted representations to scientific concepts, constructs and practices. (Paper V. p. 92)

Further, it follows from this definition that representational competence in this case can be seen as made up of ***a set*** of discrete representational competencies within a number of semiotic resource systems. Each system would have its own version of the triangle in Figure 6.14, e.g. graphs (R_{GRAPH}), diagrams ($R_{DIAGRAM}$), mathematics (R_{MATH}), … etc. Note that R is made up not only of the sum of these discrete representational competencies with respect to a particular concept, but also entails the ability to fluently move *between* each of these different representations of the concept to create what Airey and Linder (2009) term a critical constellation of resources with respect to the object of interest. Such movement may occur both within a given representational system—transformation—and across different representational systems—transduction—see again the earlier discussions in Sections 3.4.6 and Section 6.1. Having defined representational competence within the theoretical framing of this thesis, a logical follow-up task is to apply this definition to a specific area of undergraduate physics so that its usefulness for physics educators, as a guide for how to practice and develop students' representational competence, can be judged.

As discussed in the Preface and Chapter 1, the area of graphs in the area of 1-D kinematics was identified as a particularly difficult representational system for introductory physics students to work with.

The iOLab device, with its set of disciplinary and pedagogical affordances was also available for this case study (C)—see Section 5.2.2. This time it was used as a kinematics cart with a wheel sensor tracking the rotation of the pilot wheel, with the information transducted to the three standard graphs (position-time, velocity-time, acceleration-time) used in 1D-kinematics to communicate concepts of motion. Graphs in physics in the area of 1-D kinematics was consequently chosen as an illustration of the usefulness of the new definition of representational competence. This exercise also served another purpose, to test and broaden the extent of applicability of the conceptual framework being used in this thesis.

First a brief discussion about graphs in the area of 1-D kinematics, from the viewpoint of social semiotics, is relevant at this juncture, since a reader may legitimately ask why such an old topic in PER is revisited, and what new understandings around students' difficulties in this area could be offered by this thesis.

6.4.2. Graphs in 1-D kinematics – a social-semiotic analysis

Students' difficulties with graphs in 1-D kinematics are well described in PER—see, for example Goldberg & Anderson (1989). Moreover, proficiency in interpreting, using and producing graphs is recognised universally by physicists as key to developing disciplinary understandings across a wide range of topics. The main difficulties students have with graphing can be broadly summarised as challenges with connecting graphs to physics concepts, and problems connecting graphs to the real-world—see the early work by McDermott, Rosenquist, & van Zee (1987). Recent studies at university level have shown that graphing in 1-D kinematics in physics continues to be problematic for students, despite them being taught this topic at high school—see Planinic, Ivanjek, Susac, & Milin-Sipus (2013), Bollen, De Cock, Zuza, Guisasola, & Van Kampen (2016), and Ivanjek, Susac, Planinic, Andrasevic, & Milin-Sipus (2016).

The generic affordances of graphs in 1-D Kinematics

Since the social semiotic-derived framework used in this thesis deals with disciplinary knowledge and its representation, a good starting point for a description of representational competence in graphs (R_{GRAPH}) in 1-D kinematics is to carry out a *semiotic audit* of the generic possibilities for meaning-making that graphs afford in this area. The idea is to then analyse the ways in which these generic affordances are used within physics to make specific disciplinary meanings.[40] This has resulted in what is referred to as a *disciplinary semiotic audit* (Airey & Eriksson 2019). Interestingly, the three disciplinary-specific graphs typically used in this area were found to leverage the exact same generic affordances of the semiotic system, but used them to make very different disciplinary meanings.

[40] See Airey & Eriksson (2019), who showed with the example of the Hertzsprung-Russel diagram from astronomy, that even for experts in a discipline, the linkages between the generic affordances of a semiotic system and the disciplinary meanings folded into them are not always self-evident

The type of graph we are analysing has four quadrants because each variable can have both positive and negative values—see Figure 6.15.

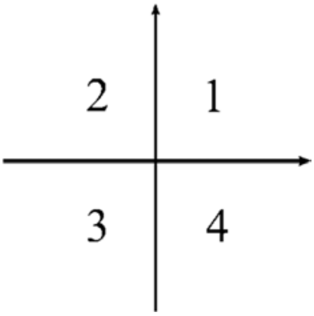


Figure 6.15. The four quadrants of a generic graph. (Paper V, p. 93)

A disciplinary semiotic audit of the graph system in 1-D kinematics

Limiting analysis to the first quadrant there are eight separate types of generic shapes that can be leveraged for meaning-making in 1-D kinematics (see Figure 6.16).

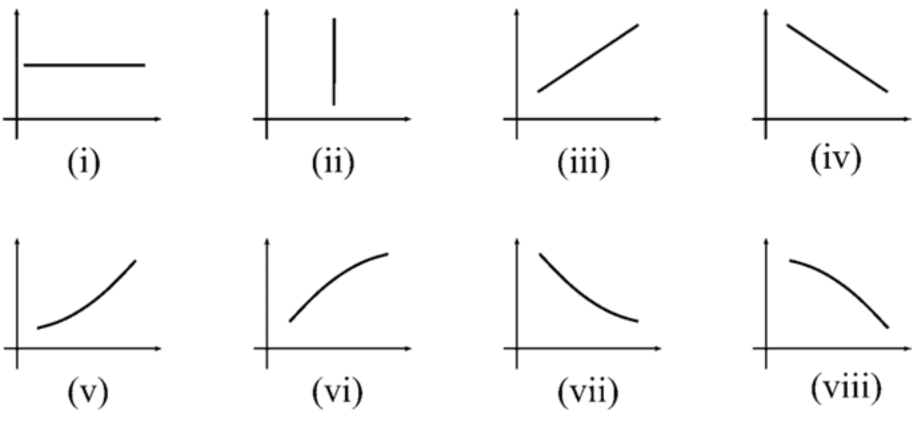


Figure 6.16. The eight generic shapes: (i) straight line horizontal; (ii) straight line vertical; (iii) straight line increasing to the right; (iv) straight line decreasing to the right; (v) increasing concave; (vi) increasing convex; (vii) decreasing concave; (viii) decreasing convex (Paper V, p. 93)

These eight shapes represent the semiotic material, or "building blocks" that can be assigned meaning within this system—essentially any curve may be constructed from combinations of these eight shapes. Note that the shapes can potentially be repeated in all four quadrants. Note also that a curve crossing any one of the axes also has the potential to mean something specific in a physical sense. Here, a graph that passes through the origin is a special case where both axes are crossed simultaneously. These, then, are the generic affordances (Airey & Eriksson, 2019) that can potentially be leveraged by physicists to represent physical quantities.

From generic to specific—what do graphs communicate in 1-D kinematics?

Physics-specific descriptions of any phenomenon usually involve a set of physical quantities, measurable or derived, that have been agreed, by the discipline, to "stand for" the salient aspects of the phenomenon. As a subsection of physics, kinematics models the motion of objects. This entails understanding how *position* (r), *velocity* (v) and *acceleration* (a) vary with *time* (t). In 1-D kinematics at high school and introductory university levels these four variables communicate a complete picture of an object's motion in a straight line.

Within the single semiotic system of graphs, these four basic scientific concepts have come to be represented using three particular graphs—*position-time* (r-t), *velocity-time* (v-t), and *acceleration-time* (a-t). For physicists, the three graphs communicate how an object's motion is changing, which in turn represents an object's *state of motion*, e.g. stationary, uniform motion, uniformly accelerated motion, etc. In these three graphs, time is placed on the horizontal axis, and, since time (unlike position, velocity and acceleration) is not usually negative in physics experiments, this means that in 1-D kinematics we are usually only interested in quadrants 1 and 4 in Figure 6.15. Given this focus on just two quadrants, the eight shapes in Figure 6.16 yield 8+8=16 generic possibilities for meaning-making per graph. If we ignore for the moment the meaning potential of the crossing of the axes, there is then a total of 16 x 3 = 48 generic possibilities that students potentially need to be able to interpret and produce across the three graphs in order to be representationally competent in graphs in 1-D kinematics. Following the proposed definition of representational competence, each of these meaning-making possibilities would also need to be linked to real-world situations and the associated kinematics concepts. An example is presented below.

Consider the following real-world motion:

A car moving along a straight road slows down.

One possible set of the three 1-D kinematics graphs associated with this real-world motion and the way that physics conceptualises that motion can be seen in Tables 1–3. Notice that assigning a positive direction and a reference position is part of a process of connecting the real-world motion to disciplinary representations—in this case the three graphs. Another possible set could have negative positions and negative velocities, in which case acceleration would necessarily be positive ("slowing down" in 1D-kinematics always means velocity and acceleration having opposite signs).

Table 1. *A position-time graph of real world motion and the physics concept(s) used to describe it*. (Paper V, p. 94)

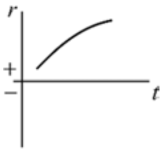
Position-time graph	*Kinematics Concept(s)*
 Convex curve, $r > 0$	Positive position Positive velocity Negative acceleration [$r > 0$, $v > 0$, $a < 0$] Note: a is constant if curve parabolic, but this cannot be seen in this particular graph.

Table 2. *A velocity-time graph of real world motion and the physics concept(s) used to describe it*. (Paper V, p. 94)

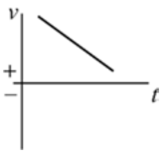
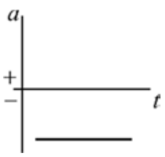
Velocity-time graph	*Kinematics Concept(s)*
 Straight line decreasing to right, $v > 0$.	*Position unknown* *Positive velocity* *Negative acceleration* *Uniformly accelerated motion* [$v > 0$, $a < 0$]

Table 3. *An acceleration-time graph of real world motion and the physics concept(s) used to describe it*. (Paper V, p. 95)

Acceleration-time graph	*Kinematics Concept(s)*
 Straight horizontal line $a < 0$.	*Position unknown* *Velocity unknown* *Negative acceleration* *Uniformly accelerated motion* [$a < 0$]

In representing aspects of the real-world motion, each of the three graphs leverages one of the 8 generic shapes in Figure 6.16 in two quadrants. Furthermore, each graph has different *disciplinary affordances*, meaning, for the purposes of this thesis, different possibilities to visually communicate essentials of the different kinematic concepts (Airey & Eriksson, 2019). In our particular illustrative case no new information is added by the *a-t* graph (Table 3), although uniform negative acceleration is made much more clearly visible by the horizontal line in the 4th quadrant (negative). This is in contrast to a purely mathematical treatment of graphs, where knowledge of the function of the *r-t* graph is all that is required—that one function contains all the information, from which the *v-t* and *a-t* graphs may be derived.

This section started out by defining representational competence in terms of the ability to interpret and produce a set of disciplinary-accepted representations of real-world phenomena and link these to formalised physics concepts. Thus, in this characterisation, full representational competence in graphs (R_{GRAPH}) for 1-D kinematics would entail being able to interpret and use all of the 48 possible graph/shape combinations to describe different kinds of real-world motion and link these to kinematics concepts. Describing real-world motion in this way also involves the ability to combine the different generic shapes to make complete graphs. Furthermore, the three graphs are linked, so that a particular shape on a position-time graph will be associated with specific shapes on velocity-time and acceleration-time graphs creating an interconnected system of "allowed states".

Returning to the visualisation of representational competence in Figure 6.14, the results of the semiotic audit can be applied to create a specific triangle for representational competence in graphs (R_{GRAPH}) for 1-D kinematics which involves interpreting and producing three types of graph that need to be appropriately associated with both kinematics concepts and real-world motion (Figure 6.17). For the full disciplinary semiotic audit of the graph system in 1-D kinematics within the definition of representational competence proposed, please see Appendix C.

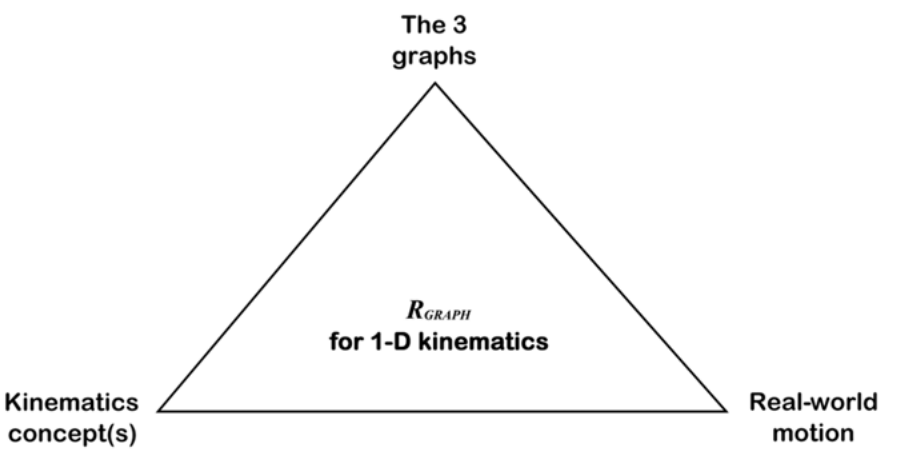


Figure 6.17. Representational competence in graphs (R_{GRAPH}) for 1-D kinematics consists of modelling real-world motion by linking features of three graphs to the kinematics concept(s) (Paper V, p. 96)

Leveraging the definition of representational competence (*R)*, Figure 6.17 offers then a template for how representational competence in graphs (R_{GRAPH}) for 1-D kinematics may potentially be practiced and developed, i.e. a way to operationalise the definition. This leads to the first research question for Paper V:

Using this definition, what kind of tasks might be used to systematically develop and practice representational competence in the area of graphs in 1-D kinematics?

In the particular area of graphs (R_{GRAPH}) for 1-D kinematics, the semiotic audit suggests the different meaning-making possibilities of the three graphs (position/time, velocity /time and acceleration/time) need to be linked to real-world motion and kinematics concepts. As may be deduced from the complexity of the full semiotic audit—see Appendix C—, this is not a trivial learning challenge for students. Based on the definition of representational competence, a systematic development would involve students being provided with one vertex of the triangle in Figure 6.14 and being asked to generate the other two vertices. For developing R_{GRAPH} in 1-D kinematics, then, tasks need to be created where students are provided with one vertex of the triangle in Figure 16.7 and asked to generate the other two. Logically, this would entail three separate tasks where each task begins with a different vertex of Figure 16.7.

6.4.3. Operationalising the definition

This section presents how the definition of representational competence was operationalised. Three open-ended tasks were designed in order for students to develop and practice representational competence in graphs (R_{GRAPH}) for 1-D kinematics. It must be noted here that following the semiotic audit, these tasks can *only begin* to develop students' representational competence. This is because there are 48 possible generic meaning making shapes (plus the crossing of the axes) across three graphs that students need to appropriately coordinate and associate with real-world and physics concepts.

Task 1

Given a situation with real-world motion, observe the shapes of the three graphs and explain these in terms of kinematics concepts.

Task 2

Given a formal verbal description of how a kinematics concept changes over time, generate an example of the associated real-world motion and predict the shape of the three corresponding graphs.

Task 3
Given the same generic shape in each of the three graph types, interpret each graph in terms of its related kinematics concepts and produce the associated real-world motion.

Note that as well as purposefully starting from a different vertex of the triangle in Figure 6.17, the tasks also become successively complex.

This leads to the second research question for Paper V.

To what extent does the implementation of these tasks appear to develop the desired representational competence?

Open-ended tasks designed around the iOLab
The designing and delivering of the tasks to develop representational competence in graphs in 1-D kinematics formed the basis of Case Study (C). As discussed in Section 5.2.2, the tasks were given to a class of Swedish university students on a physics teacher undergraduate program.

In order to implement and assess the three tasks with students, the iOLab was again used. Essentially, the open-ended tasks revolved around students engaging with the iOLab both as a system for producing the disciplinary representations (the three graphs) and as a tool to produce the real-world experiences (observing and effecting the motion of the sensor-box), which then presented the opportunities for students to carry out the tasks in the way it was conceptualised, i.e. practice and develop R_{GRAPH} in 1-D kinematics. One of the sensors is connected to a wheel on the underside of the iOLab. This measures the position of the device at any given time and can therefore be used to produce the three graphs that describe the motion of the device—see Figure 6.18 for a screenshot of the iOLab interface screen for a recorded run with the wheel sensor selected and the iOLab sensor-box dragged across the floor at constant speed in a straight line by a toy car (see Figure 6 in Paper V, p. 98).

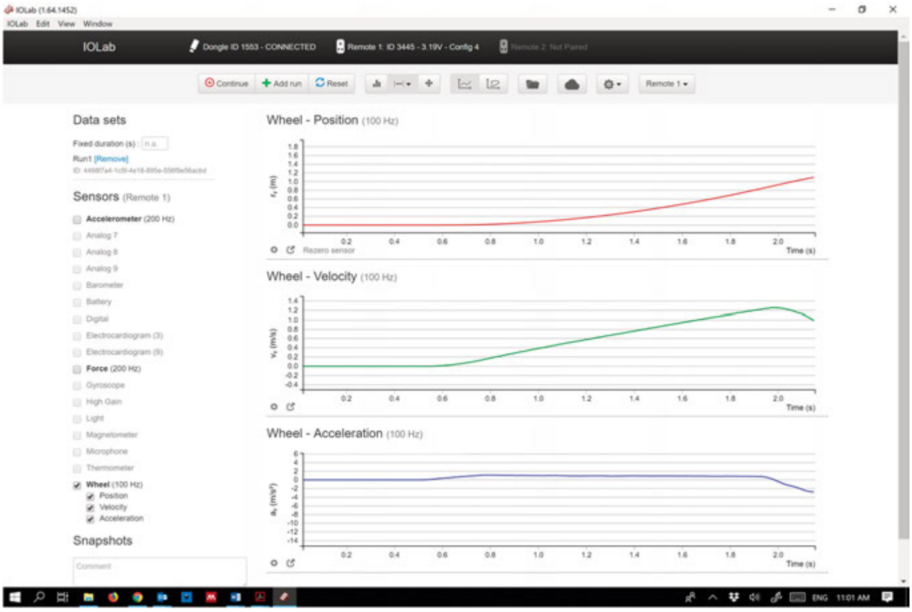


Figure 6.18. The iOLab interface screen with the wheel sensor utilised to track the motion of the sensor-box and transduct that meaning to the three motion graphs. The red line is the r_y-t graph, green the v_y-t graph, and blue the a_y-t graph.

Due to the nature of the task, roving cameras were used to record the students' engagement with the iOLab, and the other resources made available to them (for example, the toy car) and those in the room (the tables were used as flat and inclined surfaces for the student-designed experiments to solve the tasks). Based on the previous findings reported for Case Studies (A) and (B), the research team were aware of the importance of the (sometimes brief) interactions between student pairs and facilitators, for it is then that students get the opportunity to articulate their understandings, and for teachers to check such learning. For example, this chapter has already provided a theoretical basis, supported by empirical evidence, for the importance of transduction as a sign that learning has taken place in these kinds of learning situations. Given the open-ended nature of the task that required students to move around the venue, a roving camera was used to record the interactions between the students and with the facilitators. Section 5.2.2 describes the data collection methods used for Case Study (C).

The three iOLab tasks described below are variations of some of those proposed by Selen (2013) for working with the iOLab system.

Task 1 (starting with real-world motion vertex)

In the first task a toy car was tied to one end of the iOLab sensor box and pulled across a table or the floor, at constant speed in a straight line (see Figure

5.4). Students were simply asked to observe the motion, inspect the outcomes for the three graphs on the computer screen, and finally, explain the motion in terms of the kinematics concepts. Here, we leveraged the transduction function of the system to produce the graphs for the students—see Paper XX. This meant that at this stage the students only needed to *interpret* the graphs made by the system, rather than having to *produce* the graphs themselves. A follow-up aspect of this task was for facilitators to join the pairs and suggest changes to aspects of the real-world motion. Students could then offer predictions and explanations for the new shapes that would result for the three graph types.

Task 2 (starting with a kinematics concept vertex)

In this task, the students were simply instructed to engineer a situation in which a stable and repeatable *constant acceleration* for the iOLab would be achieved—most of the participating students quickly chose to leverage gravity by raising the laboratory table at one end to create an inclined surface and let the iOLab (without the toy car) roll down the incline. Students were then asked to *predict* with explanations what the three graphical readouts would look like in terms of the shapes and directions of the graphs produced.

Task 3 (starting with the graphs vertex)

This task required the students to move the iOLab in such a way as to produce the same pre-set shape for each of the three graph types in turn (see Figure 6.19). Students first interrogated the graph in terms of the kinematics concepts described, before predicting the necessary real-world motion. The students could then move the iOLab and observe the graphical output. Note that this is a very complex task when the graph shape is inspected with the semiotic audit—the combination graph shape involves eight different segments, each meaning something different in the real-world domain of the motion of the iOLab sensor-box. It was therefore anticipated that this activity would be the most challenging for the students.

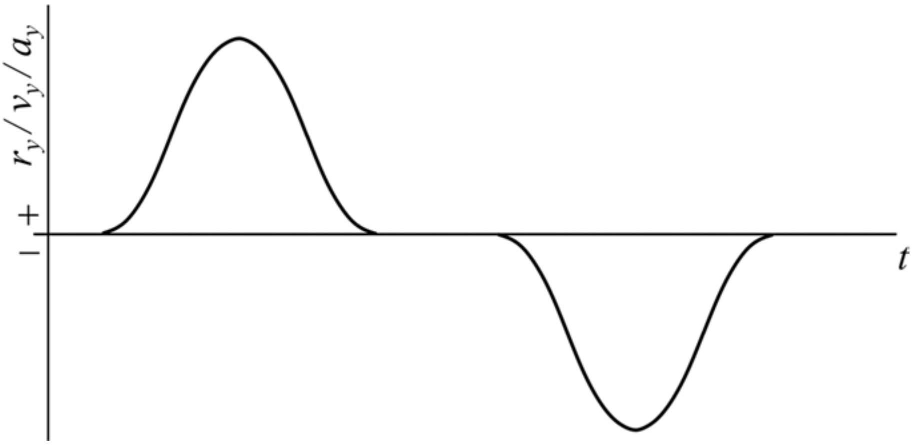


Figure 6.19. The shape students were asked to produce for each of the three graph types. (Paper V, p. 99)

With these tasks, the first study question was answered—recognising and leveraging the affordances of the iOLab system, and applying the theoretical perspectives derived from the conceptual framework for this thesis, the tasks were believed to be ideal for students practising and developing their competence in working with graphs in 1-D kinematics. The following section reports on the empirical findings related to the second study question—to what extent were the three tasks observed to develop the needed representational competence.

6.4.4. Results and discussion

As explained in Section 5.2.2, only selected excerpts constitute the multimodal transcript for this study. These vignettes were selected to illustrate the ways in which the students engaged with the three tasks. The reader is referred to Section 6.1.4 where the particular style of presenting the transcript excerpts are provided. These transcript excerpts have been simplified from our full multimodal transcript (see Appendix B for one vignette as an example)—for example, words replace snapshots and superimposed graphics to signify actions and gestures, together with using different styles of brackets. -

Note that since the students' representational competence was not tested before the three tasks, only the shifts in representational interpretation and production that the students exhibited can be reported on. However, it was often evident to the researchers, particularly during their engagement with the students,–that representational competence was being developed and practiced.

Task 1

The students managed to successfully complete Task 1 by explaining the shapes of the three graphs and correctly deducing the kinematics concepts from the observed real-world motion—essentially, that the toy car was pulling the iOLab device across the floor or table at a constant velocity (see Figure 6.18 for a representative set of graphs produced by the iOLab system for the observed motion). At this point two facilitators engaged with one student pair to probe their level of representational competence. The students were first asked to imagine the iOLab box still towed by the toy car but with the car now moving from right to left across the laboratory bench, instead of left to right as before. They correctly concluded the graphs would be the same. One of them pointed to the printed set of axes on the iOLab to correctly conclude that the sensor would "not notice" the difference. Thereafter, the students were asked to imagine the iOLab itself being rotated through 180 degrees so that it was in effect "towed in reverse". Starting by tracing the original graph line in the air, the student then correctly imagined and traced out the new shape (see Figure 6.20).

Figure 6.20. Student correctly deduces the shape of the new graph, tracing it out in the air. The student's left hand is deliberately positioned and shaped (holding a something in space) to signify the point on the r_y-t graph corresponding to the position at which the first run would have been stopped and the iOLab sensor-box hypothetically turned around, so that the toy car now pulls the sensor-box in reverse. The right hand is shaped like the tip of a pen (signifying a drawing action) and traces the deduced straight line graph that would result. (Paper V, p. 100)

When asked to vary the real-world system, the students could begin to correctly visualise the graphs themselves (up until this point the graphs had been generated "automatically" for them by the iOLab system). Furthermore, the students could also correctly predict the new velocity graph—first a horizontal line in the 1st quadrant (positive), followed by a horizontal line in the 4th quadrant (negative). Analytically, this was taken as evidence of the development of R_{GRAPH} within 1-D kinematics.

Task 2

The students quickly created a sloped surface by simply balancing two feet of the laboratory table on the edge of the skirting board of the room. Some students articulated their choice by explicitly referring to creating a "free-fall" situation; an example of leveraging their prior physics knowledge about constantly accelerated motion. Their improvisation—not free-fall, but a sloped surface—was evidence that they could successfully conceptualise the kinematics concept of constant acceleration and produce an appropriate real-world instantiation. After one pair had completed the task, the facilitator with the video recorder was called. A Socratic-like dialogue ensued. One student (S13) explained the graphs in the following way:

S13: *The position graph is showing exponential growth, because it goes faster and faster, more and more increase* [simultaneously moving hand in an ever-steeper gesture] *in the position. And the velocity is a constant slope, as it gains the same increase in speed over time, one can say. And, as expected, the acceleration is a constant over time*

One of the facilitators then asked the students what the graphs would look like if the iOLab were rolled down the sloping surface with the device turned around, "*and let it go in the same way*". The following interaction ensued:

S14: *So the direction in the graph would be, opposite, ...but the minus… would still be the same*

S13: [S13 makes a hand gesture and traces a concave decreasing curve in the 4th quadrant similar to shape vii in Figure 6.16]

F3: *So can you just go one by one?* (Gesturing to the three graphs the students have produced—by making the iOLab move in the way they set it)

S14: *OK, so, this* (referring to the r_y-t graph) *would still have an exponential curve*

[S14 points directly at graph on screen and traces a decreasing convex curve similar to shape viii in Figure 6.16 with index finger]

F1: *And where would it start?* (referring to the line the student just traced with hand over screen)

S14: *Umm, oh, it will still start at zero. But, it will be like…*

[S14 again traces the same curve, but much more clearly, starting index finger at the origin, and tracing a convex decreasing curve in the 4th quadrant spanning the width of the screen]

... in the negative, uhh, (chuckles), *call it …*

F1: *Yeah, the, the ne-.., 2nd quadrant* (referring to the 4th quadrant—remember the students only have 2 quadrants on their graphs)

S14: *And then, the velocity, it'll just like turn like this*

[S14 first aligns her hand with the increasing straight line (shape iii), then mirrors it to be a decreasing straight line in the 4th quadrant (shape iv)].

So we will have still have the same slope, but negative. As with the position, it would just be in the negative.

F1: *And start with?*

S14: *Start with zero. And with acceleration, we would have a negative acceleration.*

F1: *So, it would be negative…?* (F1 earlier led students to read off the approximately constant value of the positive acceleration from the graph.)

S13: *Minus 1.*

S14: *Negative 1.*
F1: *Negative 1, yeah.*

If one overlooks the "incorrect" everyday usage of the word "exponential"—a term commonly used by the students as a kind of "generic label" for a concave shape (rather than a particular mathematical function)—then, this interaction becomes a powerful demonstration of how the students practiced representational competence while carrying out the tasks. Firstly, S13 could explain with physics-specific descriptions the meanings of the graphs for the motion of the iOLab down the incline. Interestingly, when asked about the reversal, S13 first draws the new graph incorrectly choosing a concave decreasing shape. However, S14, then, takes over, and using hand and index finger, traces out the correct shape (convex decreasing) over the top of the first graph. Here, the original graph functions as a persistent semiotic resource and acts as both a placeholder for the first student's meaning making and as a coordinating hub for new meaning making (see Section 6.1.5). As such, the persistence of the graph provided the facilitators and the students with opportunities to check and modify understandings. For the description of the new velocity graph, the students begin to spontaneously introduce new resources—here hand gestures specifically generated over the graphical plot. In Section 6.1.6 it was argued that the introduction of such new semiotic resources provides signs of student learning taking place (Papers I and III). This is clearly illustrated in this excerpt, a hand laid along a line of constant slope, accompanied by physics-specific speech. For the new acceleration curve, the usage of the single value (minus one) signified the students' understanding of the new curve being constant, but in the fourth quadrant.

Task 3

This was understandably the most challenging task for students and indeed the introductory semiotic analysis suggested this would be the case. This is because the "double-bump" in Figure 6.19 involves four of the generic shapes from Figure 6.16 in each quadrant (total eight). Moreover, the meanings of these generic shapes change radically across the three graphs.
Only the analysis of the students' explorations and experiments to obtain the *r-t* graph is presented here.

As a first attempt, the participating student pair started again with a table raised at one end, as was the case for Task 2. They rolled the iOLab device up the slope, starting the run from rest, pushing it to achieve a smooth but short acceleration before letting it go, and then stopping it when the box had rolled back to the starting position. Analytically this demonstrates that they had adequately conceptualised the different phases of the motion (the kinematics concepts) for obtaining the "single bump" shape graph. However, they expressed having "big trouble" with getting the "negative bump". They explained how they first, after a short pause, just turned the box around and repeated the same motion—here they leveraged their earlier realisation of the function of the wheel sensor and the printed axes from the first two tasks. A second idea was to let the iOLab simply roll past the original starting point and stop it lower down the slope—thus creating the negative position. However, the students observed that that would need a different "force" in order to produce the shape that was asked for in the task. One facilitator then suggested they try to move the box on a flat surface and just use their arm—a suggestion they readily accepted. For their first attempt, S13 pushed the box in four perceivably different stages forwards and backwards starting and stopping at the same point. S13 then inspected the graph (only a single bump) then with the support of the facilitator S1 shifted the starting position to the middle of the table. S13 now moved the iOLab backwards and forwards in one direction from the starting point (negative positions) and, after a short pause, repeated the same motions in the other direction (positive positions). The students quickly realised their "mistake"—either the box should have been turned around, or the motion should have started in the opposite direction first. Aided by timely facilitator inputs, the students' words and actions demonstrated an ability to quickly make the required adjustments to their real-world motion experiments, in order to achieve the desired shapes for the position-time graph. Analysis and discussion about this pair and other pairs of students' engagements which followed obtaining the graph shapes for the v_y-t and a_y-t graphs, are excluded from this thesis. The hope is that this data will lead to a further publication in the future, along with a comparison with a South African group of university students who also did the same iOLab wheel sensor task.

6.4.5. Summary and conclusions

In this section, the social semiotic lens as applied in the conceptual framework of this thesis was used to suggest a nuanced definition of representational competence that may be used in physics:

Representational competence (R) is the ability to appropriately interpret and produce a set of disciplinary-accepted representations of real-world phenomena and link these to formalised physics concepts.

This definition was chosen because much of physics involves the creation of disciplinary concepts from real-world observations. This characterisation was summarised in the triangle in Figure 6.14.

The usefulness of the proposed definition of representational competence was tested by applying it to one particular semiotic system (graphs) in 1-D kinematics. As a first step, a *disciplinary semiotic audit* was carried out to establish what representational competence would entail for this particular area of physics. This is illustrated diagrammatically (in Figure 6.17). Based on the semiotic audit, three iOLab-based tasks were developed with the explicit intention of assisting students to develop and practice representational competence in this area. There is evidence from the student interactions documented in Case Study (C) that successful completion of these tasks goes some way in assisting students to acquire the intended representational competence. However, no claim is made that after completing these tasks, they develop full representational competence in this area.

In the literature there are several examples of research and curricula focussed on encouraging movement between multiple representations in science learning, similar to those described in this thesis—for example, the *Physics Active Learning Guide* of van Heuvelen and Etkina (2006) and the work of Stern, Aprea, & Ebner (2003) and Duval (2006a, 2006b). Through Case Study (C), one way of thinking about representational competence has been offered (in the form of the triangle in Figure 6.14) within which one can understand why such approaches are successful and how approaches in new areas might be developed. Thus, although the illustrative empirical work presented in this thesis deals with the application of our definition, to the developing and practicing of representational competence in one particular semiotic system for a very particular area of physics, it is argued that there are potentially broader lessons to be learned.

For example, could the description of how the three tasks were constructed provide guidance for teachers on how to help students develop and practice representational competence in other semiotic systems for other areas of physics and indeed science education in general? Whilst this is beyond the scope of this thesis, it does however suggest possibilities for future research.

A note about transduction and transformation

Further to what I write about transduction and transformation at the end of my preface and the beginning of Chapter 1, I wish to point out the following: The episode (see the discussion under Task 2, Section 6.4.4 above, or that on page 101 in Paper V) in which the student pair were able to deduce the appropriate graphs by inspecting the other graphs, is an example of where a (successful) *transformation* took place—here, the students were able to correctly interpret the information from the position-time graph, and then correctly deduce what the shape and quadrant of the velocity-time graph should be. Not only that, it appears that it is the *transductive link* between the graph system and the real world, which facilitated the ease with which the students were able to make this correct transformation. The students showed evidence of their understanding by introducing their own resources (deliberate hand gestures accompanied by verbal explanation) and in so doing demonstrated developing competence by making the link between the real world and the graphs for themselves (see the caption for Figure 6.20). There appears therefore to be an interesting relationship between transformation and transduction, especially when the roles of these different shifts in meaning-making are considered from the perspective of developing representational competence.

When it comes to *transduction* (i.e. meaning-making across semiotic systems or 'transmodal' meaning-making), as previously discussed (see Sections 3.4.6, and 6.1), meanings by necessity are added or lost. Put another way, the signmaker—as I have discussed in Section 6.1, could either be a device which represents the interests of the device maker, which is the physics community, or a discourse participant engaged in a disciplinary communicative practice—is forced to make certain semiotic choices, but must make sure these choices result in a coherent 'message' being shared. In this way, the transductions made possible in our tasks, by linking real-world phenomena to the physics-specific semiotic resources or representations that stand for the disciplinary relevant aspects we want students to learn, train students to notice what is important from a physics perspective. In the context of the VTL, the transductions performed by the students in the tasks generated the required variation, but in a dynamic sense. Speculatively, students *may* then be in a much more secure position to make the appropriate *transformations*—because, if they can make the required transductions within the representational competence triangle, they can then best understand which transformations will not make sense, since each resource within a semiotic system must also be accessible through transduction in a coherent way to real-world phenomena.

This answers the question about how students may learn to discern which combinations (or "allowed states") of the three graphs are appropriate for description of a real-world motion or a state of motion in a certain context. As the semiotic audit shows, there are at least 96 (8 x 3 x 4) different possible meanings, excluding zero-line graphs and graphs crossing axes, that may be associated with the standard generic shapes across the three motion graphs in the four quadrants, which introductory students are presented with when studying 1-D kinematics.

Taking this further, Airey & Linder (2009, 2017) realised the importance of a critical constellation of semiotic resources to make learning of new physics concepts possible, and that varying the disciplinary relevant aspects of the targeted physics concepts in any given task is the only way for students to notice these semiotic resources. Further, students need to develop fluency in (the effective application of) each semiotic resource, which of necessity requires them to go through a learning process in which they progressively connect disciplinary meanings to their initial discourse imitation as they increase their disciplinary discernment. Case Study (C) has demonstrated how transduction plays a central role in the development of representational competence.

6.5. Answering the research questions

In this section I directly address the answers to my research questions and collect them together in one place. In doing so I naturally collate and summarise the information presented in this chapter and my publications. My overall research question was as follows:

> *What might transduction—a theoretical construct common in the field of multimodal social semiotics—contribute to social semiotics research work in PER?*

Here, it is clear that the introduction of the term transduction (and its parallel concept transformation) has offered PER new ways of viewing the role of semiotic resources. Before the inception of this thesis, the main focus when categorising semiotic resources within the conceptual framework discussed in Chapter 3 was the persistent/non-persistent distinction. This distinction formed the theoretical basis of the then ground-breaking notion of *coordinating hubs* put forward by Fredlund (2015)[41]. However, when Fredlund et al. (2012) discussed the differences in disciplinary affordances between a ray diagram and a wavefront diagram for explaining why refraction occurs, he was in fact talking about a *transformation*—that is, a recasting of meanings within the *same semiotic system* (diagrams).

The main theoretical contribution of this thesis is to point out that, on the whole, *transductions provide more opportunities for student learning* than transformations. This is because of the fundamental requirement that meaning must be added and/or taken away for transductions to be able to take place (see discussions in Paper III, Section 6.1, and in particular 6.1.6 of this chapter). Next, transduction introduces a dynamic aspect to learning. Before the introduction of the transduction lens, social semiotic discussions around learning in PER had typically involved three stages: 1. identifying disciplinary relevant aspects, 2. choosing appropriate semiotic resources that showcased those aspects and 3. creating variation *within* those resources to help students discern them (see for example (Fredlund, Airey, et al., 2015), and (Airey & Linder, 2017). With the introduction of the concept of transduction in this thesis, the focus has changed from creating purposeful variation *within* each of the separate semiotic resources to create a critical constellation, to a realisation that the necessary variation for a critical constellation may also be created by movement of meanings *between* semiotic resource systems—that is by transduction. As such, this thesis has enhanced the social semiotic perspective in PER by adding a second, complementary method for the creation of variation

[41] In his notion of coordinating hubs, Fredlund points out the value of a persistent semiotic resource as a permanent, unchanging hub around which other (mostly non-persistent) semiotic resources could be coordinated to form a critical constellation.

to the system already detailed in Fredlund, Airey & Linder (2015). Using this insight, further research questions were devised. Thus, the answers to questions 1-6 all stem from and are answers to my overarching research question.

RQ1: How can the role and functions of physics devices be described when applying the social semiotic lens used in this thesis?

Section 6.1.1 started with an analysis of the role of physics devices from the viewpoint of social semiotics. Principal to that analysis was the simple observation that physics devices must generate outputs that physicists can interpret. Here, the ways in which the output of such devices can be interpreted has already been agreed within the discipline. Thus, the sensors, electronic circuitry, etc. that make up physics devices all exist to perform functions to shift signs produced by environmental input to outputs within semiotic systems that physicists can work with. In this respect, three major functions of physics devices were identified. Physics devices *intensify*, *filter*, and *transduct* environmental input. Semiotically then, for phenomena that are not directly perceivable via the human senses such as magnetic field, transduction becomes critical, since by necessity the semiotic material of interest must be moved to a new semiotic system that humans can perceive. An example here is the clicking sounds produced by a Geiger Counter. This answer to RQ1 now forms a basis for answering RQ2.

RQ2: Based on the answer to RQ1, how can the concept of transduction be used in this thesis to extend our understanding of the role and function of probeware in physics teaching and learning activities?

How physicists *use* and *interpret* the outputs of physics devices is an integral aspect of physics work. To understand the ways in which physicists make meanings with devices, especially in teaching and learning contexts, one therefore needs to understand how devices themselves contribute to disciplinary meaning-making practices.

From a semiotic perspective, if students, as novices in physics, are to understand the links between the disciplinary-accepted semiotic resources used in physics and the physical world around them, they need to be given opportunities to connect the real world to its standardised representation. This necessarily involves transduction of semiotic material from the environment to standard disciplinary representations. In all three case studies described in this thesis, probeware enabled students to interact with the environment around them whilst simultaneously paying attention to disciplinary-accepted outputs. Thus, from a social semiotic perspective, the relationship between the physical world and its disciplinary-accepted representation is constantly the focus of such probeware activities and transduction is the means by which this is achieved.

Using the theoretical relationship between pedagogical and disciplinary affordance of semiotic resources (Airey & Eriksson, 2019), in an analysis of the iOLab's design with its array of sensors, computer interface and portability, etc., revealed that the system has both high disciplinary and high pedagogical affordances. Probeware, in general can be used then to both do physics and learn physics, if their generic affordances are leveraged appropriately in tasks; here again, transduction to facilitate movement of semiotic material in the system is key.

RQ3: In what ways might a transduction perspective supplement our understanding of why interactive engagement is an effective strategy in physics education?

The empirical work of this thesis has demonstrated how physics with a range of semiotic resource systems typically need *chains* of transductions (see Paper III, p. 24), especially in active learning situations such as the physics teaching laboratory. Whereas physics problem solving could be done successfully by individuals, pair work encourages meanings to be placed in the semiotic space between individuals. This generates possibilities for communicated meanings—through the production of signs—to be interrogated and disambiguated. In the case studies long chains of transductions could be seen to be needed before students could make sense of the what the resources available to them were saying about the physics/real-world relationship. This would have been impossible without the pairwork encouraging meanings to be placed in the semiotic space between individuals. The insertion of a placeholder (usually a persistent resource that holds all the meanings that had gone on before in a long learning chain) then performs the function of holding the chain together up to a certain point in a learning sequence, and further may function as a coordinating hub—as shown in this thesis—for further meaning-making through transductions in the continuing chain towards a learning goal. Thus, it is argued that it is the discussions around meanings that are enabled by interactive engagement that allow students to progress towards physics understandings through chains of transductions.

RQ4. How can the application of social semiotics help us design tasks where students gain initial access to mathematical concepts for physics without the necessity for mathematical calculation?

Using probeware, students can leverage their bodies to interact simultaneously with the environment and its disciplinary representation. Utilising this aspect, students no longer need to take readings that they then must transduct into graphs or equations in order to generate mathematical answers. Students can thus interact more directly and intuitively with physics phenomena without the need for mathematical calculation. Using this lens, it is argued that it is possible to design any number of tasks where students can "feel" their way to a conceptual understanding of a phenomenon *before* mathematical formalism is introduced. In educational contexts, where mathematical resources (especially using equations to calculate) are overvalued, tasks should be designed to force students to rather pursue chains of transduction that train their attention on the conceptualisations relevant to the learning goals.

RQ5. Using the lens of social semiotics, what is the role of student representational competence in learning 1-D kinematics and how can such competence be developed?

The work in this thesis, detailed in Case Study (C) and published in paper 5, highlights the complexity involved in becoming representationally competent in 1-D kinematics. Student representational competence in one particular semiotic resource system (graphs) was analysed through a semiotic audit of the three graphs traditionally used within this area of physics, namely position/time, velocity time and acceleration/ time. Here, it was shown that the eight generic shapes used in these graphs to represent physics knowledge together form an intricate system of meaning making that students need to be able to master (see the full analysis in Appendix C). In terms of generic meaning-making affordances, 8 x 2 x 3 = 48 specific physical meanings are potentially represented by the generic shapes in two quadrants across the three graphs (see Section 6.3.4). It was noticed that as well as the generic shapes, there are two further aspects that students need to understand before they are representationally competent. First, there are the specific physical meanings that are signified when curves on the three graphs intersect the axes. Second, a given shape on any one of the three graphs signals certain shapes on the other two graphs—this can be likened to a system of *allowed states* across the graphs. Thus, representational competence in the system of graphs for 1-D kinematics involves not only being able to interpret each shape on each of the three graphs in terms of what is happening physically, there is also the interconnected transformation aspect between graphs that needs to be considered.

In the thesis, representational competence in graphs for 1-D kinematics consists of being able to connect physics concepts, through the graphs to real world motion and *vice versa*. Having defined representational competence in terms of linking these three aspects, a method for practicing such representational competence was proposed where students would be given one of the aspects (graph, real world situation or physics concept) and be asked to generate the other two.

RQ6. How can the results from RQ5 be used to propose a generalised way of developing representational competence in physics education?

In this thesis it is suggested that representational competence (*R*) consists of a set of discrete competencies in different representational systems R_{GRAPH}, etc., adding in a holistic way (complementary and supplementary) to *R*. Transduction now is bridge between the systems, which suggests a generalised way of developing *R*.

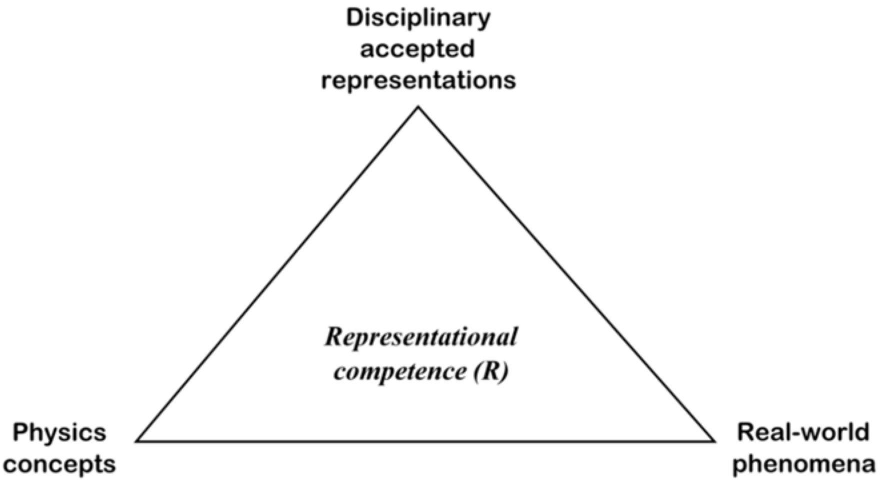


Figure 6.21. This figure is a duplicate of Figure 6.14. (see Paper V, p. 92).

Students can practice and develop representational competence in each of the discrete semiotic systems first, by linking the semiotic system to the real-world phenomena under study and the physics concept(s). Then, by having the opportunity to make linkages through transduction between the systems, students can systematically construct more holistic understandings of a physics concept.

In the next Chapter, a summary of all the contributions to the field of PER that emerged during the process of answering my research questions, is given.

7. Contributions to PER

The purpose of this chapter is to summarise the contributions of my PhD work in the field of Physics Education Research (PER). I have collated these contributions under three headings:

1. Empirical findings
2. Theoretical contributions
3. Suggestions for the teaching and learning of physics.

7.1. Theoretical contributions

This thesis makes the following theoretical contributions to the field of PER:

- The introduction of the term *transduction* into PER vocabulary to refer to the movement of meaning from one semiotic resource system to another.
- The claim that transduction is central to making learning possible in physics.
- The insight that transduction always involves addition and/or subtraction of meaning.
- Since meaning is always added and/or subtracted, transductions across semiotic systems offer important opportunities for teaching and learning in terms of helping students notice different aspects of physics meaning.
- Interactive engagement can be seen to be effective because of the need it creates to generate *communication* about conceptualisations with peers and/or lecturers.
- Seeing as all communication involves representation(s) of some form or another; once produced, representations can be interrogated by peers and lecturers, which in turn leads to conceptualisations being tested and refined.
- Transduction is one of the means by which meanings can be interrogated and disambiguated.
- With its focus on transduction, this thesis introduces a new dynamic understanding to the UUPER theoretical framework. Building on the Variation Theory of Learning, it is the movement of meaning *between* semiotic systems that generates new opportunities for student learning. This is complementary to the existing theory, where lecturers generate variation

for their students by leveraging the *different disciplinary affordances* of individual semiotic resources to form a critical constellation.

This thesis adds the following theoretical understandings about the role of devices in physics, particularly in laboratory settings:

- Physics devices are designed so that they *intensify*, *filter*, and/or *transduct* environmental input—in order to make it more readily available to the human senses (e.g. a Geiger counter's audible clicks).
- Semiotically, the interpretation of the physics meaning of the output of any physics device has already been agreed upon by the discipline—only certain meanings are allowed.
- A large part of learning to work with physics devices therefore involves students coming to understand how device outputs should be interpreted.
- Probeware tools are particularly effective in teaching and learning of disciplinary content when they combine high pedagogical affordance with high disciplinary affordance with respect to the intended learning goals.

This thesis makes the following theoretical contributions in the area of physics work with multiple semiotic resource systems:

- *Representational competence* is defined as the ability to appropriately interpret and produce a set of physics-specific representations of real-world phenomena, and link these to formalised physics concepts.
- This representational competence is made up of the sum of a number of *discrete* competencies (i.e. $R_{TOTAL} = R_{GRAPH} + R_{MATH} +$ …etc.), and also involves being able to move *fluently* between each of the different representations.

This thesis makes one further theoretical contribution to the pre-existing social semiotic framework used and developed for this thesis:

- Persistent semiotic resources (diagrams or graphs for example) can function as *placeholders* that facilitate cognitive off-loading of all the meanings that have been made up to a given point.

7.2. Empirical findings

This thesis presents the following empirical findings:

- Students' spontaneous introduction of new semiotic resources (i.e. their own transductions) can be a sign that learning is taking place.
- Introductory physics students may conceptualise Cartesian coordinate systems as being fixed in a standard orientation (as shown in textbooks).

- The thesis demonstrates how an appreciation of the movability of a Cartesian coordinate system can be developed *without* the need to engage in mathematical calculation.
- Probeware tools that facilitate direct physical interaction can allow students to leverage their proprioception (i.e. the knowledge of how their body is moving) while simultaneously focussing on the output from the tool.
- In a learning context where mathematical resources are highly valued, students may adopt a purely mathematical approach, even though a task may have been designed to avoid the need for such calculation.
- Representational competence (as defined in this thesis) can be effectively developed by designing tasks that specifically target movement of meanings between real-world experiences of phenomena, disciplinary accepted scientific representations, and the physics concepts they are linked to.

7.3. Implications for the teaching and learning of physics

Building on the theoretical contributions and empirical findings discussed, this thesis makes the following recommendations for physics lecturers:

- Encouraging student transductions can help students to learn physics more effectively
- Lecturers should leverage transductions to check their students' conceptions.
- Lecturers should choose interactive engagement as the basis for designing tasks targeting conceptual understanding.
- If used, probeware tools should be assessed in terms of their disciplinary and pedagogical affordances with respect to the learning goals of the intended task.
- Tasks that leverage student proprioception should be used where possible.
- Physics lecturers should endeavour to map out the potential chains of transductions that would be required for an idealised version of the learning task they present. Then, by paying attention to actual student transductions physics lecturers can better understand where students are in their reasoning, and, if need be, nudge the students towards more fruitful avenues (but note the following point).
- Students may still be learning in transduction chains that do not lead to the solution of the physics problem at hand. Physics educators should therefore contemplate this possibility before intervening to correct students' "unproductive" avenues of investigation.

- Lecturers should be aware that their own transductions to non-disciplinary resources (such as gestures) may assist students in making the desired connections between resources.
- Lecturers should give careful consideration to what persistent resources might be able to function as placeholders for off-loading meaning within a given task.
- The possibility of such placeholders functioning as a coordinating hub for other resources in continued meaning-making should also be considered.

8. Future work

The findings in this thesis and their implications for the teaching and learning of physics, presented in the previous chapter, open the way for a number of exciting areas for future research work.

The three cases studies that formed the empirical base of this thesis represent the tip of the iceberg of a wide range of physics concepts that introductory students find problematic. However, the analysis of these three cases has produced interesting generalised perspectives on how students may learn better with probeware tools in interactive engagement laboratory tasks. A natural continuation of this research would therefore entail expanding this perspective to other types of learning situations. When King (1966) envisioned a "shoebox of sensors that could be used to measure almost everything" (Tinker, 2000, p. 1), it was only a pipe dream. Now that such devices have actually become available and are beginning to be widely adopted in physics curricula (see Ansell, 2020) there is much work that still needs to be done in understanding the roles and potential benefits of probeware devices, such as the iOLab. In my many years of teaching there have been a number of areas that my introductory physics students found particularly difficult—for example, waves and oscillations, sound, heat, energy, etc. In future work I would like to explore the pedagogical and disciplinary affordances of the iOLab when working within these topic areas.

In Case Study (C) I examined the development of Swedish students' representational competence in the area of graphs in 1-D kinematics. Given the surprising differences in student approaches that were observed between Case Studies (A) and (B), I plan to carry out a comparative study where the same task is given to South African students.

One thing that I did not have time to explore in Case Study (C) was the role of other semiotic systems in the development of the holistic representational competence (R) as it was defined in this thesis. In particular, from the perspective of my initial research interests, what role may the mathematical system play in attaining R in 1-D kinematics? A further question is how such mathematical competence may be built upon the competence practised and developed for the graph system. Would it, for example, be more efficient from a learning perspective to focus on graphs first, and scaffold the mathematics on top of the understandings gained in connecting graphs with the kinematics concepts, or would it be better to develop the discrete competencies in parallel?

This thesis began with an interest in what might be gained by the introduction of the distinction between transduction and transformation into Physics Education Research. The findings of the thesis clearly point to transduction as an integral component of multi-representational work with a range of semiotic systems, however, the role of transformation and its relationship to transduction remains a complex one, and hence calls for further research. For example, in the case of the use of graphs in 1-D kinematics, the issue of transformations between the three graphs (position-time, velocity-time and acceleration-time) poses further interesting questions. The semiotic audit of the graph system suggests that students need to develop a sense of which combinations of graphs describe a real-world motion—in the thesis these relationships between the three graphs are discussed in terms of allowed states. Performing derivations and integrations of the mathematical functions associated with the graphs presents one way of ensuring that the transformations are consistent. However, the difficulties students have with these transformations appear to be more conceptual than mathematical. Being able to perform the calculations does not mean students can interpret the provided solutions correctly. One question for future work is whether the ability to perform (and understand) such transformations is dependent on students having first experienced transductions.

9. Sammanfattning på svenska

Denna avhandling bidrar både teoretiskt och empiriskt till forskning kring lärande i fysik på högskolenivå. Teoretiskt tar avhandlingen en socialsemiotisk ansats. Socialsemiotik handlar om hur olika grupper utformar och upprätthåller specialiserade sätt att kommunicera inom den egna gruppen. Därmed intresserar sig denna avhandling för hur fysiker kommunicera fysik till varandra. Forskningen är viktig eftersom fysik anses vara ett svårt ämne att behärska och denna svårighetsgrad har tidigare kopplats till den mängd av olika semiotiska system (diagram, bilder, matematik, språk, etc.) som fysiker oftast behöver koordinera i sina beskrivningar av fysiska fenomen (Airey & Linder, 2009).

I avhandlingen undersöks vad introduktionen av en teoretisk gränsdragning mellan två olika termer *transformation* och *transduktion* skulle kunna ha för betydelse för forskningen om lärande i fysik. Transformation är förflyttning av mening inom *samma* semiotiska system—t.ex. mellan ett diagram och ett annat diagram—medan transduktion är förflyttning av mening mellan två *olika* semiotiska system—t.ex. från bild till matematik. Avhandlingen framhåller att transduktioner är mer värdefulla i lärande situationer eftersom de alltid innebär att information läggs till och tas bort. Dessa förändringar kan användas i lärandesituationer för att dra studenternas uppmärksamhet till vissa aspekter av ett fysiskt fenomen.

Redan 1966 såg John King framemot en tid då man skulle ha en "skokartong" fylld med detektorer med vilken man skulle kunna mäta nästan vad som helst. Idag är Kings samling av mätenheter i en enda box verklig—och i betydligt mindre format dessutom. I de tre fallstudier som undersöks i denna avhandling används just en sådan box som heter *iOLab*. De två första fallstudierna handlar om studenter som ska lära sig om flyttbarheten av koordinatsystem genom att undersöka Jordens magnetfält. Studenterna kunde få fram riktningen av magnetfältet i rummet genom att få en av koordinaterna i sin iOLab box att överensstämma med fältets riktning. Här visar fallstudierna att studenter inledningsvis såg koordinatsystemet som fixerad i en vertikal position (såsom de framställs i textböcker). Avhandlingen visar hur en förståelse för rörligheten av ett koordinatsystem kan utvecklas *utan* att man behöver ägna sig åt matematiska beräkningar. Detta är viktig eftersom för fysiker är en av de s.k. *disciplinary affordances* av ett koordinatsystem dess flyttbarhet—det är hur fysiker förenklar sina beräkningar. Övningen i fallstudierna visade sig vara ett effektivt sätt att hjälpa studenterna att först förstå att ett koordinatsystem går att sätta upp hur man vill och därefter kunde de se värdet av denna flyttbarhet för fysiken.

I den tredje fallstudien undersöks 1-D kinematics där studenterna får förflytta sin iOLab på olika sätt och koppla förflyttningen till olika grafiska framställningar och fysiska koncept. Här studeras studenternas s.k. *representational competence*. Representational competence definieras som förmågan att på ett lämpligt sätt tolka och framställa en mängd fysik-specifika representationer av fysiska fenomen och länka samman dessa till formaliserade fysikbegrepp. I avhandlingen beskrivs denna representational competence som bestående av summan av ett antal diskreta kompetenser (dvs. $R_{TOTAL} = R_{GRAPH} + R_{MATH} + \ldots$etc.), och involverar även förmågan att röra sig *obehindrat* mellan varje representation. Representational competence (så som det är definierat i denna avhandling) kan därför på ett effektivt sätt utvecklas genom att designa uppgifter som specifikt riktas mot förflyttandet av meningar mellan: verklighetsbaserade erfarenheter av fenomen, inom disciplinen accepterade representationer av fenomenet och de fysikbegrepp som de länkas till.

Vidare lägger avhandlingen fram ännu ett teoretiskt bidrag—nämligen att i studentdiskussioner kan beständiga semiotiska resurser (till exempel diagram eller grafer) vara värdefulla som *platshållare.* Dessa platshållare fungerar som en kognitiv avlastning för alla de meningar som har avhandlats fram till en given tidpunkt i en studentdiskussion.

Att kunna identifiera när lärande pågår har alltid varit svårt för didaktiska forskare. Ett av avhandlingens empiriska bidrag är att studenters spontana introduktion av nya semiotiska resurser (dvs. deras egenhändiga transduktioner) kan vara ett tecken på att lärande håller på att ske. Här föreslås att lärare bör utnyttja dessa transduktioner för att kontrollera studenternas föreställningar. För att åstadkomma detta bör fysiklärare sträva efter att kartlägga de potentiella transduktioner som krävs för att utföra de lärandeuppgifter de ger sina studenter. Genom att sedan uppmärksamma de faktiska transduktionerna kan fysiklärare bättre förstå var studenterna är i sitt resonemang och, om det behövs, försöka rikta in studenterna mot mer produktiva vägar.

Slutligen, inom fysik anses matematiska beskrivningar som de mest värdefulla resurser vi har för att beskriva fysiska fenomen. Men matematisk skicklighet utan en konceptuell förståelse av fysiken är inte meningsfullt. Mot denna bakgrund visar avhandlingen att fysikstudenter rent av kan *övervärdera* det matematiska tillvägagångssättet. T.ex. i en av fallstudierna envisades studenter med sina försök till matematiska lösningar trots att uppgiften hade utformats för att undvika behovet av just en sådan beräkning, varför det föreslås att lärare bör arbeta med konceptuell förståelse *innan* man introducerar matematiska beräkningar. Avhandlingen ger flera exempel på hur sådana övningar kan utformas.

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Appendices

Appendix A

Appendix A
Full multimodal transcript of a selected student pair's interaction – Case Study (A)

Table 4. *Transcription data - speech/action/event of selected student pair, S1and S2.*

Event sequence/ major events	Time	Speech Transcribed	Action / Gesture / Interaction
F2 introduces device; students receive and read instructions, then calibrate IOLab	**0 – 06:50**	Mostly in Swedish … - e.g. S2 moves IOLab away from iron…S1proceeds with calibration.	▪ Students interact with instruction sheet; S1 alone handles computer; looks like S1 and S2 interact to clarify instructions, etc. S1 at this stage does most of the handling of device as well as the calibration procedure on laptop screen.
F1 gives a mini-lecture introducing task – to measure the magnetic field in the room	**06:50 – 07:15**	*I think now it's time to tell you what you'll be doing today because until now you've only been calibrating the device. So today, you'll be measuring the magnetic field in this room. So for this purpose we have here; this device has many sensors inside (points to IOLab) and one of these sensors is a magnetic field sensor which measures the magnetic field in …*	
	07:15 – 07:30	… *so the magnetic field is like a vector quantity – has a direction and size – and so this device has a sensor which measures the magnetic field density in*	▪ "*vector*" - F1 uses hands to indicate a vector (hands makes gesture resembling an elongated object / or arrow?) ▪ "*direction*" – uses right hand to gesture forward

		all three directions, so in three different directions…	▪ "*size*" – uses both hands with open palms (as if holding an object in hands) ▪ "*three different directions*" – uses right hand with three fingers pointing in mutually orthogonal directions (hand gesture which represents right-handed coordinate system within discipline).
	07:30 – 07:47	*… so once you're inside you can choose the magnetometer sensor; if you have set it up, you should be able to click on the magnetometer and it will display a graph which will update as time passes, like in real time it will measure three components…*	▪ "*magnetometer sensor*" – F1 points to boy/S2 (bg1) group's laptop screen ▪ "*if you have set it up"* – F1 runs over to boy/S2 group (subject of this transcription) and looks at their screen (perhaps to see if they've got that screen or have been able to follow and clicked the correct button) ▪ "*which will update …in real time*" – uses hand to sweep across from left to right (graph 'direction' for time – horizontal) ▪ "*three components*" – uses right-hand coordinate axes gesture again.
	07:47 – 08:35	*… and so your task for today is to measure the magnetic field in this room, first on the top of this box – on the top of the box you received; this is just to distance it from other disturbing vectors such as metal … legs of this table and so forth… ; and then when you do that you should represent how the magnetic field in this room*	▪ F1 grabs large red cut-out arrows designed and made by Filip for activity. ▪ "*top of this box "* – points to IOLab and white box ▪ "*metal … legs …*" – points to table legs ▪ "*represent…where it is pointing"* – uses one red arrow and rotates it in multiple directions ▪ "*using these arrows*" – holds up arrows ▪ "*tape to side…*" – holds arrow next to white plastic box, rotates it to represent any possible directions

		looks like, where it is pointing […in-distinct…] using these arrows, so you can use a piece of tape and this arrow to show where the magnetic…, how the magnetic field looks like at the point where you measured it, so you can tape this arrow to the side of your box to show where it's directed. So your task is to actually figure out from the three components where the magnetic field is pointing.	
S1&S2 engage with instruction sheet to activate graph.	**08:35 – 08:58**	***F1**: OK … is … any questions … maybe I wasn't clear … OK, so, each group gets one arrow … starts handing out red arrows to groups …, Students speaking in Swedish*	
	08:58 – 09:30	*Still speaking Swedish, reading instructions out loud in Swedish; **S1** tries to get graph screen going by engaging with laptop; **S1&S2** reads instructions sheet and S1 engages with laptop screen and touchpad;* ***S1**: Acceleration magne/i… speaks in Swedish* ***G**: Sensors list; then click record* ***S1**: Asks question in Swedish,*	▪ **S2**: *"Sensors list …then click record"* – looks at screen ▪ **S1**: "*asks question in Swedish*" – … looks at instruction sheet. ▪ **S2**: "*record, what is record*" – looks intently at screen ▪ **S2**: "*what is record…*" – S1 responds with clicking on correct buttons (selects and clicks correct sensor tick-box)… gets graph screen going. S2 excited and utters happy word in Swedish ▪ **S1**: "OK …" – reads instructions again, (inaudible)

		S2: *Mmmh, there … record, what is record…* ***S2***: *Ah-sa-yeaah* (happy expression) ***S1***: OK …	
Group starts working with IOLab	**09:30 – 10:18**	***S2***: *We should be showing the direction of this*	▪ **S2** grabs red arrow
		S1: *I don't know, how do we read that, how do we know that*	▪ **S1** looks at screen
		S2: *(reading instruction sheet) and to fix the arrow that represents the direction, chuckling.*	▪ **S2** suspends red arrow in front of laptop screen, chuckling and looking at screen (!)
		S1: *Ohh, I guess, I don't know, mmm, what happens if we move it … Oh Shit, look at that …* ***S2***: *chuckles (hah, hah, hah)*	▪ **S1** grabs IOLab and rotates IOLab while looking at screen, both look at screen
		S1: *Holy crap, holy crap … Ummh, yeah, moving it changes it of course, so I guess we could figure out by the amount* ***S2***: *No, I guess …*	▪ **S2** takes IOLab and rotates it
		S1: *You see the blue line went up to the top* ***S2***: *Yeaah, ok.*	▪ **S2** is still rotating IOLab ▪ **S1** points at graph on screen.

		S1: *Yeah, I don't really know what this tells us.*	
Group explores different orientations of IOLab	**10:19 – 11:10**	***S1***: *Wait, what did you just do now? What did you move it from?*	▪ **S1** reflects (looks to) on information on screen.
		S2: *Sorry, from the standing position to this one.* ***S1***: *From y being down to z being down, or to x being …* ***S2***: *No, to x being up…* ***S1***: *To x being up yeah,* ***S2***: *Now is x down*	▪ **S2** takes IOLab and what follows are successive manipulations (e.g. *y* up, *x* up, etc.) based on instructions from S1.
		S1: *Right, change it back, and change it back to y being down; right, look at that; now change it back to x being down* ***S2***: *[indistinct]* ***S1***: *No, I meant x being up, sorry, from y being up to x being up.* ***S2***: *Ok, y being up now* ***S1***: *Yeah, to x being up.* ***S2***: *And now x being up*	▪ **S1** pointing to graph on screen; alternately looking at position of IOLab and screen…
		S1: *Nah .. that wasn't … must've been x being down to …[indistinct]..there. I think it was like this … if you look at*	▪ **S1** now gets off his seat and stretches over to manipulate IOLab himself

		the screen, look at the screen; y is down, and x is up … ah nah actually it wasn't, ahh, crap…	▪ **S1** orients laptop screen so that **S2** can see graph better, and manipulates IOLab from his sitting position (stretched over) ▪ **S2** chuckles.
Group figures out meaning of hori-zontal axis on graph; and starts unpacking vertical axis	**11:11 – 11:45**	***S2***: *This is, this is a frequency? Mm...mh*	▪ **S2** point with red arrow at screen.
		S1: *Yeah, … ahh, I don't know really know… I don't know what the y-axis and the x-axis (pause) stand for .. ah, wait…*	▪ **S1** wrings his hands (frustrated/ thinking/reflecting?), then does something on computer and gets an answer apparently.
		S2: *Oh wow!* ***S1***: *It's just …* ***S2***: *The time*	▪ **S2** now moves her head closer to the screen to inspect graph more closely.
		S1: *Yeah, it's the time, … this have to be the time of course…*	▪ **S1** sweeps his right hand across screen in horizontal motion
		S2: *And that must be the frequency then* ***S1***: *Yeah*	▪ **S2** points at screen again with red arrow (using it as pointer – distance away from screen) and moves it in an upward motion (clearly tracing out the vertical axis)
		S2: *No, but can you have a negative frequency?*	▪ **S2** points red arrow at screen again.
		S1: *I don't know.*	▪ **S1** shrugs shoulders and lifts left hand (palm up) in a manner indicating he does not know.

		S2: *Why do we get three different things?* ***S1***: *I don't know.* ***S2***: *OK!* ***S1***: *[indistinct mutter] ? "so moving on then" in musical tone …*	▪ **S2** lifts red arrow way from screen ▪ **S1** shakes his left from side to side. ▪ At end **S1** stares intently at screen in apparent deep contemplation…
S1 picks up IOLab away from white box and moves it in space without rotating it (up/down; forward/backward)	**11:45 – 12:48**	***S1***: *OK, wait, hold on, I have an idea.* ***S2***: *chuckle …*	▪ **S1** picks up IOLab (smiling); first moves it forward and backward, up and down – no rotation; then holds it stationary while rotating it (about *y*)
		S2: *…but, … let's put it close to the… no, then, no…more colours, [indistinct]…hah-hah, close to the chair*	▪ **S2** looks at screen and grabs IOLab while S1 still holds on to it;… (wanting IOLAb to be close to screen) ▪ **S1** moves IOLab towards and away from laptop screen while looking at screen (no rotation).
		S1: *Right, if you turn it like that* ***S2***: *That's cool, … cool, mmmm (high pitched).*	▪ **S1** holds up IOLab (*x*-axis vertical) and rotates it 90° about *x*-axis (clockwise from above), then back to original position again; then rotates it 90° anticlockwise.
		S1: *What does it mean, with the lines are straight? Does it mean that it's in the field, or in the direction of the field is facing, maybe…?* ***S2***: *I don't know; …*	▪ **S1** rapidly moves left hand backward and forward (right hand still holding device), then looks at IOLab directly in front of forehead.
		S1: *If we change that…* ***S2***: *[indistinct]…than go where we get a negative umm number there…*	▪ **S1** holds IOLab in front of forehead, +*x* up; looks at screen below bottom of IOLab box and rotates it about *x*.

			▪ **S1** then rotates it back, then about *z* (IOLab now upright …+*y* pointing up)
		S1*: Well now y (or why?) z can't be true cause they're always going straight regardless of which way you hold it* ***S2****: OK* ***S1****: So that would then (or wouldn't?) make sense*	▪ **S1** points with forefinger at screen; ▪ **S1** then looks at IOLab in front of face.
		S1*: I don't know…*	▪ **S1** tapping side of IOLab
		S1*: [indistinct] …on paper …*	▪ **S1** puts IOLab back on top of white box, and starts reading instructions
Group trying to figure out what to do with graph values, and class teacher (F2) arrives.	**12:48 – 13:45**	***S2****: Ah-hah, I think we need to use Excel right …* ***S1****: How?*	▪ **S2** looks intently at **S1** (searching for answer).
		S2*: …maybe … to create like err …* ***S1****: I mean, I… can't even understand the graph or the diagram* ***S2****: …to create, … to see the slope, for me to see the slope..*	▪ **S1**'s right arm comes up at **S2**'s suggestion (indicating pointlessness?) ▪ **S1** gesticulates despondence/frustration (?) with arm gesture
		S2*: Because then here if we have different [pause]ummh… like if we look*	▪ **S2** points at screen with pen. ▪ **F2** arrives and peers over front of screen.

		at that specific line and then you record the different numbers… (F2 peers over screen) … and then you calculate the slope by using Excel …	
		***S2** (to **F2**): Can you use Excel?* ***F2**: Once more.* ***S2** (to **F2**): Can you use Excel to calculate the slope?*	
		***F2**: Errr... ah, yes, but you don't, you don't need to.* ***S1**: Yeah, I don't understand why we would...* ***S2** (to **S1**): Ok, well, thanks for your support!*	▪ **F2** expresses neutrality (?) opens hand in arm gesture to side.
		***S1**: … Well, I don't understand why we would need to. I don't even understand what we need to do with the graph or the diagram?* ***F2**: You will figure it out in a few minutes*	▪ **F2** points at **S1**.
		***F2**: … if you start just playing with it…* ***S2**: Ah well, we've done that, … we've played with it for a long time…*	▪ **F2** points arm at IOLab and makes a manipulation gesture (fingers cupped as if gripping something and twisting wrists cw and acw)

		S1: *Yah, we've tried, … the lines just came…but we can't really, or I mean...*	
F2 explains meaning of axes wrt the magnetic field, colours of lines on screen; students use this to unpack the meaning of axes values … concludes with coming up with strategy to set an axis to zero. Filip (F2) joins at end of section.	13:45 – 15:24	***S2***: *Why do we get a negative line?* ***F2***: *Have you seen this …?* ***F2***: *Here is…* ***S2***: *Yes, we have…* ***S1***: *…the y-x, and …*	▪ **F2** picks up IOLab and points to set of coordinate axes printed on cover of device.
		F2: *Yeah, … so, the y is showing the magnetic field in the y-direction.* ***S1***: *Ah, OK.* ***S2***: *Ah-hah.*	▪ **F2** point with finger at screen graph (clearly pointing to one of the coloured lines on the screen). ▪ **S1** gets up off seat to inspect graph line more closely.
		F2: *So it says that you have a magnetic field in this direction right now that has …* ***S1***: *-50… OK.*	▪ **F2** moves hand in upward motion (repeats a few times) with index finger pointing up. ▪ **S1** gets off seat again to get closer to screen.
		F2: *…yes, … and you also have in x-direction, have… this value, and in z, z is going opposite you …* ***S1:*** *OK* ***S2***: *And so,… so the red one is umm..., and the blue one is y, and …* ***S1***: *…Ahhh, ok, ok, I understand.* ***F2***: *All the time, yes.*	▪ **F2** performs similar hand motion, but this time in direction of the +*x*-axis (horizontally, since IOLab's *y*-axis pointing vertically upward); and *z*… ▪

		S2: *Ah-hah.*	
		F2: *So, if you change, if you move it around, the y shouldn't change…* ***S2***: *Mm-mm* ***S1***: *Nah, the y doesn't change.*	▪ **F2** carefully and slowly rotates IOLab around *y*-axis (keeps base flat on white box top) ▪ **S1** looks at screen and then to IOLab
		F2: *The y is in the same direction all the time …* ***S2***: *S1ut then, so the x is umm, that's red.*	▪ **S2** holds red arrow horizontally (to represent *x*-direction?) ▪ **F2** continues to slowly rotate device about *y*; students looking at screen.
		S1: *Try and get the …, if we keep y the same, and we try swivelling it around, try and get z to …or try and get x to zero… [indistinct]*	▪ **S1** point at IOLab and makes a swirling motion with same hand. ▪ **F2** leaves. ▪ **S1** points at screen ▪ **S2** swivels device as **F2** did.
		S2: *Which one is x?* ***S1***: *Umm, the red one.*	▪ **S2** squints her eyes at screen (as if instruction is not clear); continues to swivel device about *y*. ▪ **S1** gets off seat to get closer to screen and answers **S2**.
		S2: *The red one; … is that a guess, or (guffaw)?* ***S1***: *No, it says here.*	▪ **S1** simply looks at screen and makes no attempt to show partner what he means.
		S2: *Whaaat?(smile)* ***S1***: *Up, stop!* ***S2***: *Sorry …*	▪ **S2** keeps swivelling. ▪ **S1** tries to grab device, **S2** prevents him and holds on. **S1** returns to looking at screen. **S2** looks at screen and

		S1: *Hold on, …if I ..* ***S2***: *Whooaa, mm-m (mouth sound for gentling saying no)… Now* ***S1***: *No.* ***S2***: *This, good, see .. Hah-hah .. No*	is attempting to get red line to zero herself (not waiting for instruction from **S1** to stop turning).
		S1: *It's not!* ***S2***: *Ok … laughs.* ***S1***: *There, … roughly.* ***S2***: *That's nice!* ***S1***: *There we go…*	▪ **S1** takes over IOLab from **S2** and swivels until he gets *x* close to zero according to his liking.
F4 joins group. Helps students to start understand-ing the meaning of positive and nega-tive axis values (wrt the direction in which magn. field is pointing)	15:24 – 18:32	*S1:… Uhhhm, that means that umm, in the y-dir'n, theee magnetic [shield ?/ indistinct] is errr… because it is nega-tive right now, it should be positive in the other directions, …*	▪ **S2** smiles at Filip **(F2)**, prompting **F2** to join group. ▪ **S1** looks at screen, then device, swivels wrist so that hand and index finger points up.
		S1: *…so, uhh wait, is it facing up or down right now?* ***S2***: *It's up, it's up …* ***S1***: *don't swivel it, don't swivel, it was on zero for a reason … right, there we go.*	▪ **S2** grabs IOLab and starts swiveling it. ▪ **S1** intervenes and stops her, replacing device to origi-nal position (where *x* was zero). ▪ **F2** listening and observing.
		S1: *Mmm, OK, x is zero at the mo-ment, and err y is -50, we have iso-lated the z-axis. So, it must be facing …*	▪ **S2** smiles at **F2** (and sneaks view at S1) ▪ **S1** starts indicating direction of magnetic field ("ar-row") but stops halfway through gesture.

		S2: *S1ut, that is towards you then.*	
		S1: *Yeah, I guess, yeah, the arrow must be facing us but we don't know how it's facing up or down.*	▪ **S1** now confidently pulls hand from IOlab (perpendicular to *x*-dir'n) with fingers pointing in direction of field.
		F2: *x is zero, which means it's nothing, so everything is in this plane.* ***S1***: *Yeah, exactly.*	▪ **F2** points to set of axes printed on backside of IOLab. Uses hand to sweep in direction of the *y-z* plane (perp. to *x*) ▪ **S1** nods in agreement.
		F2: *y-z plane; and, mmm.* ***S1***: *And y is -50.*	▪ **F2** points and looks intently at device (seems to be at axes)
		F2: *Yah, so it must be on the other side of zero …* ***S1***: *Exactly, yeah.* ***F2***: *… pointing down…*	▪ **F2** uses two fingers to point below axes-vertex to indicate "below zero" for *y*-axis; moves hand downward.
		F2: *And the z is .., here is z-axis pointing that direction.* ***S1***: *Yeah.*	▪ **F2** points at *z* axis on device: looks intently at an imaginary line that lies along *z*-axis going into and out of IOLab; uses hand to gesture along this line (in dir'n of +*z*).
		F2: *If you have…laughs… x, y, z, like a screws.* ***S1&S2***: *Yeahh..* ***S2:*** *Okeyyy?*	▪ **F2** produces RH finger representation of a set of RH coordinate axes; points to each finger in cyclical order while calling out *x, y, z.* ▪ **F2** makes the gesture of a screw (twisting right hand – RH Screw rule)

		S1: *OK, uhhh, question is why, cannot really comprehend is, which, how do we know which side is positive and which is negative from the box.*	▪ **F2** observes with hands clasped, exhibiting great interest in discussion between students, but does not intervene or interject.
		S1: *I mean ahh, I guess we can just try it out. Right now y is -50. And if we change it?* ***S2***: *Yeah, so it is +50, ok.* ***S1***: *Yeah, now it is +50, so ok.*	▪ **S1** flips device so that *y*-axis now points down (orientation wrt *x* the same) ▪ **S2** and **S1** together look at screen. ▪ **S1** flips device back to original position with +*y* pointing up.
		S2: *S1ut, if you moved it on the sides, like horizontally?* ***F2***: *Mmm..mm mm* ***S2***: *We change, it will be zero…ah-hah.*	▪ **S2** flips device with *y*-axis now horizontal. Smiles and looks at screen. ▪ **S1** looks intently at screen.
		S1: *No, it is not zero.* ***S2***: *Almost … now it's zero .. but see, it's zero, when I tilt it this way.*	▪ **S2** still swivelling device about *x*-axis.
		S1: *Nothing is zero.* ***S2***: *Yeah, it is.* ***S1***: *It's close, but it is not zero.* ***S2***: *Now it's zero.* ***S1***: *It's still not zero.* ***S2***: *Yes, it is.* ***S1***: *It's not!* ***S2***: *Laughs … it is zero … it is! Now!*	▪ **S2** now tries to get values back to zero by swivelling device. **S1** looks back and forth between device and screen. ▪ **S1** argues with **S2** about zeroness of value.

		S1: *[indistinct]* ***S2***: *OK, ok.* ***S1***: *Right, now it's roughly.* ***S2***: *Now z is zero.* ***S1***: *Yeah.* ***S2***: *And x is umm, x is the same as y from the other side.*	▪ [**F2** in background using pointing arm gestures (right angles between to arms, etc.)]
		S1: *It's still not zero though…(after few seconds) Now it is yeah.*	▪ **S1** stretches over to IOLab still on top of white box and simultaneously swivels device to get *z*- axis value closer to zero.
		S2: *Sorry.*	▪ **S2** bumps table, device moves a little, and **S1** stretches over and repositions device to centre of white box top.
		[some time elapses] no speech / action	▪ **F2** repositions camera – angle now able to capture manipulations with device better
		S2: *Which way is this arrow pointing?* ***S1***: *Mmm, I'm kind of confused right now.* ***S2***: *Yeah, welcome to the club.*	▪ **S2** picks up red arrow ▪ **S1** taps fingers on table impatiently.
			▪ **F3** asks **F2** to assist elsewhere, **S1** & **S2** looks around.

Student group tries to make sense of what they've observed so far: meaning of zero in a particular direction; F2 joins group – uses arm gestures (addresses meaning of zero and arbitrariness or convenience of choice of coord. axes)	**18:32 – 21:02**	***S1****: I think it would be [indistinct (zero?)] if we had y facing up.* [Comment: **S1** referring to x-axis(?)] ***S2****: S1ut why, .. why does, why does x become zero this way?* [Comment: this is incorrect based on positioning of IOLab … so she must be referring to when they swivelled IOLab in upright position until *x*- was zero … later comments by S2 confirm this – need to get *x* to be zero]	▪ **S1** stretches over and repositions device with +*y* up. ▪ **S2** looks at screen then points with pen at IOLab.
		S1*: Umm, if x is zero it means there's no …* ***S2****: So, so, it's all, it's all …[indistinct]* ***S1****: … there's no magnetic, … there is no reading from the magnet sensor in the x-plane, which means uhh…*	▪ **S2** makes up and down motion with arm.
		S2*: It's, it's all in this, from z?* ***S1****: What?* ***S2****: It's all going towards us then?* ***S1****: Mmm, no; if it's zero, it would mean that, hold on, it would mean that it's …* [some time elapses]	▪ **S2** points pen at area on device where set of axes are printed – at vertex of *x*-&*y*-axes lines is a circle with z printed inside) ▪ **F1** assists group directly in front field of view of S2&S1, and mentions word "plane" with accent – **S2** & **S1** looks up and listens briefly.

		S1: *I'm not sure if it's either, it's in the plane or it's … as far from the plane it could be, or far from the [in-distinct] … I'm not sure.*	▪ **S2** is clearly not listening to **S1**, rather tuning in on F1's discussion with group across room. **F1** is making twisting hand gestures which **S2** is focussing on. ▪ **S1** throws right hand up and puts hand over mouth. ▪ **S2** picks up device, moves it around a bit and watches screen.
		F2: *F2his is, errr, difficult?* ***S1***: *Slightly, yeah.* ***F2***: *Mmm-mm*	▪ **F2** joins group. Peers over top of laptop to see screen.
		S1: *It's confusing … If you put it like we had it, and don't move it again! … Hold on.*	▪ **S2** places device back on top of box. ▪ **S1** stretches over and repositions device to previous position where +*y* was up and *x*-value zero. **S2** puts hands together in front of her mouth and chin, and looks around while **S1** is manipulating device.
		S1: *Now we have x is zero, or close to zero, and y is -50 as we had before, and z is -20 …* ***S1***: *I don't exactly know what that means, but, it should give us some-thing.*	▪ **S1** taps on table as he talks and looks at device twice while stating values; rocks on chair.

		***F2**: If we start just with a two-dimensional system;* ***S2**: Mm-m* ***F2**: … and this is x- and this is y …* ***S1**: (echoes **F2**'s words) … this is x- and this is y- …* ***S2**: Yah*	▪ **F2** first points at small axes on device (fingers circle close to area); then steps back from table slightly and points right arm horizontally away from his body, and left arm vertically up [Comment: before directing arms, **F2** looked at axes again seemingly to align his arms with *x*-& *y*-axes printed on device.
		***F2**: If I move in this direction, what is the value of y-?* ***S1**: Zero.* ***F2**: Zero*	▪ **F2** points right arm horizontally.
		***F2**: And for instance, if I move in that direction,*	▪ **F2** points right arm at a 45° angle, then drops it to talk …
		***F2**: **…** and I position my system in a way like this …* ***S2**: Still zero …[indistinct]* ***F2**: It's still zero.* ***S2**: Ahh…*	▪ **F2** now points right arm again at 45° (to horizontal) and left arm 45° to vertical (two arms perpendicular to each other roughly) ▪ **S2** looking at IOLab & screen alternately.
		***F2**: It's still zero. So, if you, you could position this device in a way…* ***S2**: Mmm … and still get … zero ..* ***F2**: … similar, similar to what..* ***S2**: Mm-mm … Ahh-hah ..*	▪ **F2** now points at device and makes swivelling gesture with right hand and fingers. ▪ **F2** again points arms at right angles to each other and 45° to horz/vert.

		F2: *And what would that mean?* ***S2***: *We would get the direction of the magnetic field?*	▪ **F2** now rubs chin with right hand and looks searchingly at students. ▪ **S2** looks at **F2** and then at **S1**, and pushes a hand forward in a directed manner with fingers together, palm vertical.
		F2: *Yes* ***S2***: *This is the…* ***F2***: *Somehow.* ***S2***: *Ah-hah, OK.*	▪ **F2** makes deliberate nodding motion with head (still rubbing chin) ▪ **S2** smiles, takes up device and moves it above white box.
		F2: *So you could reposition your own system … in a way that fits you, suits you.* ***S2***: *Yah..*	▪ **F2** makes swivelling gesture with right hand in front of his body. ▪ **S2** seems to be still listening (responds to F2's comment with "yah") but looking at screen while swivelling device.
Students now trying to manipulate IOLab so that *x*- and another axis value are zero. They try to move IOLab along axes to get zero values.	**21:02 – 25:28**	***S2***: *[indistinct]…we want the red to still be zero, but if I …* ***S1***: *It doesn't matter; we could choose any one of them to be zero.* ***S2***: *Oh no, cause we want x- to be zero.* ***S1***: *We could just as easily do it by y- being zero or z- being zero.*	▪ **S2** points at screen.
		S2: *Mmm-mm, we'll stick to x.* ***S1***: *All right, OK, fair enough.*	▪ **S2** holds device, smiles at S1. ▪ **S1** shakes head side to side

		S1: *comment in Swedish* ***S2***: *I'm trying.*	▪ **S2** manipulating device while looking at screen (in air, not on white box anymore)
		S1: *Why don't you put it up there?* ***S2***: *Cause we want it to be a zeroing position…* ***S2***: *Now, is it not?* ***S1***: *Why don't you just put it up there, and you can get a stable reading?* ***S2***: *S1ecause it has to be tilted.*	▪ **S1** points at top of white box ▪ **S2** moves device closer to box, but still manipulates with hands only (not resting on box) ▪ **S1** points at top of box again while tapping right hand fingers on table.
		S1: *I guess, if we, umm ... ahh, ok, I've got an idea.* ***S2***: *OK ... Mm-m, mm-m.* ***S1***: *If we put it up here, hold on ...*	▪ **S1** points at top of box again while tapping right hand fingers on table. ▪ **S1** stretches over, places device on top of box and positions it with y-axis up and rotates it so that *x*-value is zero (looks at screen while rotating device).
		S1: *... there x- is zero. So we know that, that's the way it should be facing to be zero, ... to have a reading of zero in the x-plane.* ***S2***: *Yah, ... so ...* ***S1***: *Don't move it, don't move it! ... And uh ...* ***S2***: *I'm sorry… So if we tilt it a bit…*	▪ **S1** sweeps hand across face of IOLab in direction of *x*-axis (right to left) ▪ **S2** tries to move device… ▪ **S1** intervenes with outstretched arm.

		S1: *Yeah, now if we try and find where, by keeping it the same in the x- … don't move it, don't move it, hold on..*	▪ **S1** & **S2** together reaches for IOLab device.
		S1: *And we try and get z- in the same as well… all right, hold on …* ***S2***: *You want z- to be zero?* ***S1***: *Yah, I'm trying to get both of them zero at the same time.*	▪ **S1** now takes hold of device on top of box and looks at screen; **S2** peers over outstretched arm of **S1** at screen.
		S1: *Isn't that z-? I don't understand, that should be z-.* ***S2***: *That should be z-.* ***S1***: *It's not moving.*	▪ **S1** moves device towards him slightly (*z*-axis is in line away from **S1**, *y*-axis still up, *x*- to his left) and looks at screen.
		S2: *Maybe, it is, err in this way …yeah, yeah, ah-hah… it's going …* ***S1***: *Nothing's changing.* ***S2***: *Thank you for your support again!*	▪ **S2** now takes hold of device and keeping orientation, slowly lifts device vertically, watching screen. ▪ **S2** smiles and puts down device
		S1: *It is changing now.* ***S2***: *Ok, Ok.*	▪ **S2** grabs device again and now tilts it about *z*
		S1: *Uhhh…*	▪ **S1** taps fingers on table.

		[Some time elapses]	▪ **S1** stretches over and manipulates the device again. ▪ **S2** tuning in on explanation given by **F1** to group across room.
		***S1**: How do we get, can we get y- to zero?* ***S2**: Yeah we can, if we switch the umm..* ***S1**: y- is … Ok, so it was -50 up here and now it is -66 down here.*	▪ **S1** takes IOLab and moves it from top of box to the table top [comment: now closer to metal bars of table] ▪ **S1** points to previous and new positions of device.
		***S2**: OK …interesting … put it on the floor? (laughs lightly).* ***S1**: Yeah, it went lower the higher you raised it.*	▪ **S1** taps fingers on table, looks at screen. ▪ **S2** takes IOLab and raises it vertically again, until she cannot raise it any further in seating position; also looking at screen.
		***S2**: S1ut, but it, it doesn't get above, right?* ***S1**: [indistinct]* ***S2**: No, it's still -50.* ***S1**: No, no, it wasn't.*	▪ **S2** now gets off seat and lifts the device even higher to make the point.
		***S2**: … but if, if …if we tilt it this way, then z- changes, see …* ***S1**: Yeah* ***S2**: If I put it on the horizontal way, see now it gets, x-, no y- is zero.*	▪ **S2** swivels device about *x*-axis (*x*-axis put in line which gives zero reading) ▪ [Comment: at end of **S2**'s manipulation, device held so that the *y*-axis pointing almost perpendicular to magnetic field – almost horizotal]

		S1: *S1ut how?*	
		S2: *S1ut why is it, why is y- zero?* ***S1***: *I don't know, … by my logic it shouldn't be working like that, or I don't know …* ***S2***: *laughs, could we get help, …see… he explains [pointing to **F2** across room] ..OK.*	▪ **S2** looks around class (for assistance?), smiles, then looks directly at camera, still holding device in position where *y*-value is zero.
		S1: *We know it's negative, and innn… right, ok, hold on, sorry.*	▪ **S1** takes device from **S2** and places it in original position (*x*-value zero, *y*- up)
		S1: *Let's just, I think we were pretty close before, we just need to …* ***S2***: *Yeah.* ***S1***: *Right, now x- is pretty much zero… So, umm …*	▪ **S1** continues to adjust position of device until satisfied that *x*-value is zero – makes horizontally tilting motion with hands (more-or-less gesture).
		S1: *And y-, we know y- is negative, so it must be facing down.* ***S2***: *Yes.*	▪ **S1** makes pointing gesture with right hand, index finger pointing down.
		S1: *And, err, we know x- is zero …* ***S2***: *…S1ut it is pointing up, yah, it must be up …*	▪ **S2** points to axes on IOLab, specifically the *y*-axis line.

		S1: *Ahh, but what I don't understand right now is what z- would mean in this case.* ***S2***: *S1ut then if we change this, would it make it this way...*	▪ [comment: *z* is pointing away from students at this point] ▪ **S2** swivels IOLab 180° about the *y*-axis; looks at screen, twists lips.
		S2: *Then the z- changes, but why, why does z- change, cause it's still this way* ***S1***: *Arrr…*	▪ **S2** uses finger to point at *z* printed on device [Comment: axis is now in opposite dir'n) ▪ **S1** shakes head, visibly frustrated.
		S2: *Can we, err ..*	▪ **S2** calls for help (**F1**) – hand up. ▪ As **F1** approaches, **S2** rotates device back to original position.
F1 joins group. Clarifies meaning of positive and negative in relation to axes on box and hence how it relates to the values displayed on the screen.	**25:28 – 29:57**	***S2***: *Umm, so we've got x- to be zero.* ***F1***: *Mm-m.* ***S2***: *S1ut then, cause this is, this is z-right, this is the way that…*	▪ **S2** puts hands on either side of IOLab pulling hands from point where *z* is printed on device outward in both directions (like tracing a thread through that point at right angles to surfaces).
		F1: *Yes, z- is pointing that way; so, it's, you showed the right direction, you just …* ***S2***: *Yeah … (smiles)… it's [indistinct … (on? only?)] … pointing that way.* *F1: That way, yes.*	▪ **F1** leans over to device (standing behind group) and points hand in fingers in direction of +*z*. ▪ **S2** now uses hand to 'pull thread' from IOLab only in +*z* dirn.
		F1: *So, you know that because of … so I will be careful, I will put it back …*	▪ **F1** takes hold of IOLab, and swivels it to face **S2**, and points to dot/circle on front face of IOLab. Then pulls

		You see this dot here? It means pointing outway. ***S2**: OK, so out, (?) then when I change it this way, then it points that way.* ***F1**: Yes, … exactly.* ***S2**: … OK, … Umm, but then umm.* ***S1**: Wait, so…umm*	hand and finger from the circle towards **S2**. Returns it to original position after explanation. ▪ **S2** now swivels IOLab around. Uses hand to pull line from dot in dir'n of +*z*. Swivels back after demonstrating.
		***S2**: We want to find [indistinct – another?] position where x- is still zero, so we can get the direction of the magnetic field.* ***F1**: Ok, so now you've managed to … no …* ***S2**: … Sorry …*	▪ **S2** takes IOLab, looks at **F1** and swivels device … smiling.
		***F1**: No, excellent idea. So, I see you are set, trying to set the thing so that you get as much things to be zero* **…** ***S1**: Yeah, …smiling* ***F1**: OK …that's a very good idea …* ***S2**: OK …*	▪ **F1** uses hand gestures to express state of knowledge (hands in cupped rolling motion .. zero?) ▪ **S2** nods at **F1**'s analysis of their strategy.
		***S1**: …we are trying to get two planes to zero, and if we get two planes to zero, we can figure out what the last one is; or, we can isolate the last one.* ***S2**:…yeah (smiling)*	▪ **S1** puts up two fingers of right hand (sign for two units)

		F1: *OK, ... good, now that you have the blue line; so what's the blue line? It's the y- right?* ***S1***: *Yeah* ***S2***: *Yes.* ***F1***: *So the y one, No, actually, no… the red one is zero right now, I'm sorry.* ***S1***: *Yeah, ... or close to zero it is.*	▪ **F1** points at screen, then comes closer to screen. ▪ **F1** corrects himself by pointing at screen.
		F1: *...close to zero, yes. So what does that mean for the field; in which direction it's* ***not*** *pointing?* ***S1***: *Umm…*	▪ **F1** uses hands in encircling motion ('family of directions').
		F1: *You've eliminated one, one family of directions ... which* ***family*** *would that be?* ***S2***: *MM-mm ... the horizontal…* ***F1***: *All the horizontal ...or just ...* ***S1***: *Wouldn't it be this way?* ***F1***: *Yes, exactly…* ***S2***: *...yeah, yeah, true.*	▪ **S1** moves hand back and forth in line of *x*-direction with index finger pointing in +*x*-dir'n.

		***F1**: So you've eliminated one direction, so it's not pointing that way or this way, because if; no, wait, it is actually not facing this way or that way...*	▪ **F1** uses arm to point along +*x* and –*x*-dir'ns ▪ **F1** adjusts body and arms to align with current line of *x*-axis given by position of device.
		***F1**: ...because if it was pointing that way, what would the value be?* ***S1**: Higher ... or lower, depending on..* ***S2**: Negative, negative* ***F1**: Negative, yes, excellent…* ***S2**: Cause it's on the negative axis ...* ***S1**: Yeah, yeah, yeah ...x- is pointing that way ... you're right ... so right now ...*	▪ **F1** keeps arm pointing in –x-dir'n. ▪ **S2** turns to **F1**, and gives answer, then turns to **S1** to explain using hand to point towards –*x*-axis. ▪ **S1** now uses hand again with finger pointing along +*x* in acknowledgement of what negative signifies.
		***F1**: So, if you now have the zero, how will you rotate this so that this value keeps being zero?...That's a very good question ..you need to keep ...* ***S1**: Yeah…umm, ok.* ***F1**: You can try.* ***S2**: If we play around.* ***S1**: ...Ok, now ...* ***S2**: So isn't it, if you just tilted it, tilted it some way.*	▪ **F1** points alternatingly at screen and IOLab. ▪ **S1** stretches over and starts manipulating device. ▪ **S2** makes tilting gesture with fingers just above IOLab while looking at **S1**.

		S1: *Now z- is zero as well.* ***F1***: *All right, ok.* ***S2***: *S1ut why is it zero though (slight chuckle)?* ***F1***: *It has to do something with how the field in this room is, how the field in this room looks like.* ***S2***: *OK…* ***S1***: *This means that the arrow should be …*	▪ **S1** tilts device about *x*-axis until he sees *z*-value to be zero as well. ▪ **F1** makes circling motion with hands to represent the magnetic field.
		S2: *…How, how does a magnetic field look like?* ***F1***: *That's a good question; we are actually now just trying to figure out the direction of it, so, where it's pointing, how it looks like is a very tough question.* ***S1***: *In that case.* ***S2***: *Must be very interesting though! (looks very happy)*	▪ **S1 continues to hold device in position (*x*-& *z*-values are zero).** ▪ After while **S1** takes up red arrow and holds it parallel to *y*-axis. Seems not to be engaged with discussion between **F1** and **S2**, rather focussed on finishing task.

		F1: *We can only represent it using arrows, so we can show where it's pointing. So then it looks like arrows to us because we choose to portray it that way.* ***S2***: *Do, do we affect, do we affect the regularity of it?* ***F1***: *Yes, in many ways we do.* ***S2***: *Yeah.* ***F1***: *S1ut right now, we're trying to figure out how it looks like if we don't disrupt it.* ***S2***: *OK.*	▪ **S2** uses hand waving motion to show 'effects on'
		F1: *That's why we give you this box so it goes away from the metal parts.* ***S2***: *S1ut aren't we disrupting it in some way?* ***F1***: *Ah, that's a good question, excellent question.* ***S2***: *Thank you.* ***F1***: *The answer would be, ...yes you are, but only by a minute amount.*	▪ **F1** points at plastic box, then at the metal on underside of table top. ▪ **S2** uses arms extended to IOLab and pulls it towards herself and then towards the IOLab to demonstrate 'disrupting' field.
		S2: *OK. Why, is that? ... How come (chuckling apologetically). Sorry, for having so many questions.*	▪ **F2** brings piece of tape to affix red arrow in direction of filed. ▪ **S1** continues to fine-tune IOLab position …

		***F1**: No, no, no, because they are very good questions. S1ecause it depends on the material properties of the matter that; kind of different types of materials affect the magnetic field in different ways…* ***S2**: OK … yeah..* ***F1**: and so, your body is made mostly out of water, and water is a very weakly magnetic interacting material … I think this question, you should keep this question for a few minutes later, and then you will start to answer this question as well* ***S2**: If I would have braces, then would … laughter..* ***F1**: Depends on what your braces are made of.* ***S2**: Ok …[indistinct] plastic … just kidding.*	

		S1: *I mean we have the, we have the direction now, because have two, we've just made two of the axes to zero, and the …* ***F1***: *So which one of those are zero now?* ***S1***: *Umm, z- and x- , meaning that it should be pointing that way.* ***F1***: *Ah, OK… explain that …*	▪ **S1** continues to fine-tune IOLab position … ▪ After **F1**'s question, **S1** takes up red arrow and points it along line of –*y*-axis.
		S1: *Like that I guess.* ***F1***: *So why did you point it downwards?* ***S2***: *How do you know?* ***S1***: *S1ecause … y- is negative. And ..if it was positive, it would be pointing upwards.* ***S2***: *S1ut we have, we have no, ah we have no z- yeah…cause it's zero.* ***S1***: *Yeah, so, the only logical explanation is that it is pointing like that, I guess.* ***F1***: *Mm-mm.*	▪ **S1** now holds red arrow next to IOLab and points it along line of –*y*-axis again.

F1's 'hypothesis' leads to testing and consolidation of ideas relating to co-ordinate systems; F1 leads students to appreciate arbi-trariness of choice of axes, confusion with what +/– means –; what zero means, etc.	**29:57 (p1) – 04:38 (part2)**	***F1**: Yah, I mean it makes sense. So you can, you can – what if you wanted to, just the x-component to be non-zero and all the others to be zero, how would you turn the thing then?* ***S1**: Uhhh, we'd have to …* ***S2**: This way, then …*	▪ **F1** points at IOLab. ▪ **S1** still holding IOLab in position with *x*- and *z*- zero. ▪ **S2** takes red arrow and points it in the direction of +***x***-axis. [*Comment: confusion between axis direction and direction of magnetic field, the quantity being meas-ured*].
		***F1**: So if you; … let's … fix this, let's … just…set this arrow; I'll give you some tape.* ***S2**: Mm-mm.* ***S1**: We have tape here.* ***S2**: We have tape here.*	▪ **F1** stretches forward, holds red arrow against side of box ▪ **S2** takes over holding re arrow in dir'n of +*y* next to IOLab, still held by S1. ▪ **F1** looking for tape.
		***F1**: Here you go.* ***S2**: Thank you, like this?* ***S1**: Yeah* ***F1**: So this is the way, ok, so now you can …*	▪ **F1** & **S2** using pieces of tape to fix red arrow to side of white box. ▪ **S1** shakes head.

		F1: *So this is your hypothesis.* ***S1***: *Yeah.* ***F1***: *So, if you now take this measurement device, ...* ***S1***: *Yeah.* ***F1***: *... and try to see if this hypothesis, like, holds, ...* ***S1***: *Yeah…*	▪ **F1** points at red arrow now fixed to white box. ▪ **S1** lets go of IOLab on top of box and leans back [*Comment: as if trying to 'take-in' the full view/picture*]
		F1: *... how would you point the measuring device if you want just the **x[emphasis]**-component to be non-zero, and all the others to be zero.* ***S1:*** *Ok, uhhmm…*	▪ **F1** points at IOLab, then emphasises "*x*" by a hand gesture [*Comment: arm in front, hand up, palm forward – a 'this' gesture*].
		S2: *We want y- to be zero ... I [indistinct] tried that ...* ***S1***: *...OK, that doesn't change y-* ***S2***: *...Let me get up [/don't think it helps(?)] ... uh, slightly* **[Check!! Not sure of S2's exact words here] 00:28 – 00:36**	▪ **S1** takes IOLab and lifts it straight up. Then lowers it to position lower than top of box and close to table surface (watching screen). ▪ **S2** takes IOLab from **S1** and gets off her seat to raise device as far as possible, while watching screen.
		F1: *So you're going up.* ***S2***: *Yeah…[light chuckle].* ***F1***: *Can you explain?* ***S2***: *Um.. well, because it's negative, it's pointing downwards, it's negative;*	▪ **F1** lifts arm and points upward with hand and index finger. ▪ **S2** uses arm, hand and fingers to point downward while looking at arrow, then upward while looking at IOLab.

		*and **[emphasis]y**- is pointing upwards, so .., but … [nervous chuckle] ..yeah?*	▪ **S2** looks and smiles at **F1** [*Comment: for affirmation/confirmation*]
		***F1**: Ok, so … no, no, it's, I'm very interesting how you're thinking, really!* ***S2**: OK .. chuckle.*	▪ **F1**'s body (nods head, comes forward slightly) and arm and hand gesture (moves rapidly up and down) to show interest in students' inputs. ▪ **S2**
		***S1**: Well, ok, if I was trying, if I were to explain how I was thinking, uhhh, the y-value we have is negative 50, and by … if we, if we lower it to the table,…* ***S2**: Yeah.*	▪ **S1** takes IOLab from top of box and places it on table (same orientation).
		***S1**: … you see it dips below minus 50 … meaning that …* ***F1**: OK…*	▪ **S1** points with index finger at screen.
		***S1**: … that increases the negative.* ***S2**: … S1ut then, ..maybe it's this, it's this..* ***F1**: … I would … I would warn you against putting it too close to iron…* ***S2**: Yeah.* ***S1**: .. AAh, ok …*	▪ **S2**, simultaneous with **F1** points at iron bar below table top while looking at **S1**. ▪ **F1** points to iron support bar immediately below table top. ▪ **S1** places device (keeping orientation) back on top of box, and looks at screen.
		***F1**: … so that I think that's like the …* ***S1**: … Ok, ok, then, um, …*	▪ **S1** lifts IOLab straight up (keeping orientation), looking at screen simultaneously.

		S2: *[indistinct]* ***S1***: *… right, well if we try the same thing, but if we go up,… nothing changes. Ok, ok,.. it must've been the..*	▪
		F1: *So what if you turned it …* ***S1***: *Nothing changes either, not the y- at least.*	▪ **S1** rotates IOLab about *y*-axis and watches screen. ▪ **S2** stretches neck to observe screen.
		F1: *OK.* ***S2***: *S1ut if.* ***F1***: *So, you turned it this way right, you turned it around the y-axis.* ***S1***: *Yeah, that… yeah, it would mean y- didn't change, … exactly.* ***F1***: *That's why …y- didn't change.*	▪ **F1** reaches across and makes a rotating hand gesture next to IOLab. ▪ **S2** grabs IOLab and flips device so that long edge is flat with box (*y*-axis now horizontal). Keeps arm stretched out with hand hovering above device [*Comment: waiting for cue*]
		F1: *S1ut if you, like flip it around other axes, for example now …* ***S2***: *Now, now, now it's zero! …* ***S1***: *Yeah.* ***S2***: *… Huh? S1ut why, ah-hah.* ***F1***: *Why is it zero? …* ***S2***: *…How come?* ***F1***: *… good question…*	▪ **F1** (addressing **S1** more directly) and pointing at what **S2** just did by flipping IOLab. ▪ **S2** takes IOLab (*z*-axis almost perpendicular to red arrow) and lifts one end of the device off surface slightly (*y*-axis now virtually perpendicular to red arrow)…points excitedly at screen.
		F1: *Where is y- pointing now?* ***S2***: *Down…*[smiles …made mistake?]	▪ **F1** points at set of axes on device and then pulls index finger in direction of +*y*-axis.

		F1: *And how is it in relation to the field?* ***S2***: *Oh! It's, it's a ninety-degree angle then.* ***F1***: *Yes.* ***S2***: *Ah-hah, that is so cool! Wow!* ***S1***: *Yeah, that makes sense.* ***S2***: *Yeeesss!*	▪ **F1** points and touches red arrow. ▪ **S2** while holding device in one hand, with other hand first pulls hand towards her (in +y-dir'n) then makes right angle and draws fingers over red arrow. S1road smile directed at **F1**. ▪ **S1** taps on table just before and after talking.
		F1: *And which one is supposed to be non-zero now?* ***S2***: *Ah, well then that's uhhm x-.* ***F1***: *Yes.* ***S1***: *Yeah-yeah.* ***S2***: *...It's, it's, um ...* ***S1***: *Yeah, x- has a value.*	▪ **F1** pointing at IOLab. ▪ **S2** points finger at device.
		F1: *And how is it [indistinct]...* ***S2***: *... It's negative, it's negative.* ***F1***: *Check it out.* ***S2***: *Umm, yeah, it is negative!* ***S1***: *Yah, we, it's [indistinct]...*	▪ **S2** looks at **F1** and gestures hand with fingers pointing up in dir'n of +*x [red arrow more or less lying in –x-dir'n*)] ▪ **F1** points at screen; **S2** leans over to screen to confirm her prediction, straightens with broad smile, looking at **F1**.
		F1: *And the other two are almost zero.* ***S2***: *Yeah!* ***S1***: *Yeah.* [less excited than **S2**]	▪ **F1** points at screen.

		S2: *Ah-hah, that's so cool (smiling).*	
		F1: *What about z-, z-axis?* ***S2***: *Uhhh…z ..* ***F1***: *z- is pointing this way.*	▪ **S1** still tapping intermittently**.** ▪ **F1** stretches to IOLab and pulls hand in line away from device, perpendicular to *xy*-plane (still held by S2 with orientation so that y- and z-values are zero)
		S2: *z- is zero, no it's positive, uh-huh?* ***F1***: *Ahhh, it is zero, it's almost zero…* ***S2***: *Ah-hah* [nods head slightly] …	▪ **S2** points at screen. ▪ **F1** leans over to peer closer at screen.
		S2: *… because, it's …(smile) because um?* ***S2***: *Yeah.* ***S1***: *Yeah*	▪ **F1** leans forward and makes a right angle with two index fingers at tail of arrow (one along *z*-axis, the other along line of arrow).
		F1: *z- and q-* [**F1** referring to field here]. ***S2***: *Ah-hah, yeah (nods).*	▪ **F1** moves one index finger along line of red arrow, the other along *z*-, until they meet in a right angle.
		F1: *So you, …, it's angles in three dimensions right, so …* ***S2***: *Ah-hah …* ***F1***: *…This can be perpendicular, and this can be perpendicular; so* **[emphasis]** ***all*** *these angles are 90-degrees, so all, like this whole …*	▪ **F1** uses two index fingers at right angle again, but this time aligns it with *z*-axis and arrow, then *y*-axis and arrow, rotating between two positions a few times. ▪ **…F1** follows up with keeping right finger aligned with red arrow and circles left hand in plane perpendicular to arrow.

		***S2**: …They would all be zero? When …90-degrees.* ***F1**: Yes, all these components are zero; so if you turn it like this …* ***S2**: …Mm-mph...* ***F1**: …It will always be zero.* ***S2**: … Ah-hah!*	▪ **S2** now makes same circling gesture with hand above tail of red arrow. ▪ **F1** points with index finger in several directions in plane perpendicular to arrow, then takes hold of IOLab and rotates it in *yz*-plane, briefly looking at screen at end of action [*comment: to check or confirm*] ▪ [*Comment: In this section, **S1** seems detached from discussion, interaction chiefly between **F1** and **S2***]
		***F1**: So what about, what about the z-; if you, if you take the z-axis, how would you set this, so(?) the field is only in the z-direction? Can you try?* ***S2**: Umm, so then I would want it to be this way?[pause] nah, nah, …*	▪ **F1** points at axes on IOLab front face; then steps back, and with arm gesture in a surveying manner [*Comment: 'floor is yours' gesture*] ▪ **S2** takes IOLab and rotates it so that *z*-axis is perpendicular to red arrow (slightly towards her and to her left), +*x*-axis pointing in dir'n of field; looks at screen. **S1** looks at screen as well.
		***F1**: So tell me where the z- is pointing first.* ***S2**: So now it's pointing this way.* ***F1**: Ok.* ***S2**: Ummm… so then it's zero…* ***F1**: So, … the one that would be non-zero, yes.*	▪ **S2** holds IOlab with one hand and makes pulling gesture with other hand from axes on face in direction of +*z* (to her left largely, slightly down and towards her, perpendicular to arrow) [*Comment: realises that this means z-value will be zero*]. Looks at **F1**. ▪ **F1** makes rotation gesture with hand and index finger pointing.

		S2: *Ohhh, I could point it this way maybe? Cause then it would be this; no, it would be negative, right?* ***S1***: *Yeahhh?…* ***S2***: *Would it?...* ***S1***: *Mmm, … no.* ***S2***: *… No, no, it's not. Ok, wait, umm … [long pause].*	▪ **S2** swivels device around (*z*-axis now pointing forward, slightly up and right relative to her body) and holds IOLab with one hand, and points with arm, hand and index finger in dir'n of +*z* (opposite in dir'n to pulling gesture). ▪ **S2** draws right hand to mouth [*Comment: not sure, pondering*]; ▪ **S1** is looking at screen; then responds to **S2**'s question ("*it would be negative, right*") and taps fingers on table. ▪ **S2's** hands hovering above device. [*Comment: uncertain*].
		S2: *S1ut I don't, I don't want it to be perpendicular right? [indistinct]* ***F1***: *Yes, so now it's pointing this way, … or that way* [Comment: referring to *z*-axis]. ***S2***: *… That way … that way, uh-huh.* ***F1***: *So it's almost perpendicular, you could say…* ***S1***: *…Yeah.* ***S2***: *…Yeah.*	▪ **S2** rotates IOLab in *x*-axis (device now with long-edge face flat on box top, *z*- almost perpendicular to arrow), looks at screen. ▪ **F1** pulls hand (pointing index finger) in –*z*, then +*z* [*Comment: correcting himself*] ▪ **S2** points in +*z*, simultaneous with **F1**.
		F1: *So, if you want to* ***[emphasis]-align*** *this vector to this vector, what should you do?* ***S2***: *Ah-hah! This way … ah, OK,* ***F1***: *Yahh..*	▪ **F1** points in order at axes labels (printed on IOLab) in direction of +*z*, then at red arrow. ▪ **S2** grabs IOLab (smiles broadly) and holds device with +*z* pointing up at an angle directly opposite to dir'n of red arrow.

		S2: *Yeah, ah-hah, [indistinct] it a negative [indistinct] because it's pointing this way and …* ***S1***: *Yeah*	▪ **S1** extends hand towards device (but **S2** grabs it first), then withdraws hand to mouth and watches screen. ▪ **F1** looks at **S1** [*Comment: to check if S1 also gets it*] ▪ **S2** looks at screen to look at value for $S1_z$; explains "*negative*" with hand and finger first gesturing along dir'n of red arrow (down at angle), then opposite. ▪ **S1** nods head up and down.
		F1: *What if you flipped it around? It's positive?* ***S1***: *Yeah, it's positive 50.* ***F1***: *Makes sense?* ***S1***: *…Yeah.* ***S2***: *Mm-mm … That's pretty cool. I mean that is cool.* ***S1***: *Yeah, ah yeah.*	▪ **F1** points at IOLab, and then makes a flipping gesture with right hand and two fingers in V-shape. ▪ **S2** flips device around y-axis so that $+z$ now points in dir'n of red arrow, looks at screen and smiles. ▪ **S1**'s right hand first over mouth (closed, loose fist); looks at screen and confirms z-value, right hand now first strokes hair over right ear lightly, then rests fingers against neck and chin, and starts pinching at cheek gently, touches ear etc. ▪ **F1** looking at **S1** intently.
		F1: *OK. So I guess, you've played around with components a little bit, so this is like; I would say this is an exercise, it doesn't really matter what this field is.* ***S2***: *Mm-mm.* ***F1***: *It's just something that has a direction in space. And you've now explored how this direction is related to your coordinate system, which you can*	▪ **F1** hands in rolling direction, then points arm at red arrow and draws hand in direction of arrow. ▪ **S2** still holding IOLab in position that gives only a z-value for *S1*, looking at **F1** smiling ▪ **F1** uses both hands and pushes down ("…*direction in space*"), then hands raised, pulled backwards and forwards ("*explored*"); hands rolling ("related to"); points at axes on IOLab ("*coordinate system*"); left hand with fingers at right angles to arm pushed into palm of right hand (*"usually the coordinate system is still*"); left

		change, right? So it's kind of strange; usually the coordinate system is still, and you change the direction… [Comment: referring to how usually in discipline we fix a coordinate system and relate different vectors in situation to this]. ***S1***: *…Yeah* ***S2***: *…Yeah* ***F1***: *S1ut you don't [indistinct:* inferred wording here*:] (always) change … the coordinate system around.* ***S1***: *… change it around.* ***F1***: *So how it's, how this vector projects onto your coordinate system; projects, just three different directions, right.*	hand with finger up makes circle then arm moves forward with pointed index finger ("*change the direction"*); rolling motion with hands ("*change coordinate system around*"); right hand first points at red arrow, then arm is moved forward with back of hand pushing down and forward ("*how this vector projects"*);
F1 now engages students (mostly S2) on questions they have had before related to the IOLab interface; leads into discussion about the nature of the earth's magnetic field; ends with F1 asking the how to figure out the angle of inclination.			

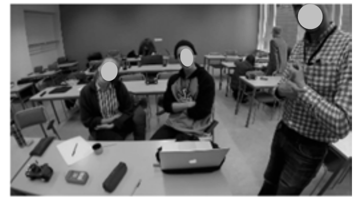
Appendix B

Appendix B

Partial multimodal transcript of a selected student pair – Case Study (C)

Faces have been blocked out to comply with GDPR guidelines.

Table 5. *Selected student pair engaging in representational competence task learning about graphs in 1-D kinematics*

Speech line #	Time	Participant	Transcribed Speech (italics = transcriber inserts)	Action / Gesture / Interaction Description	Resources/modes engaged Context	Frame capture
0	**00:00**	All	Initial pleasantries, introductions	▪ F3 had brief prior interaction in which S13 mentions the word reference to explain graphical features; F3 calls F1 to record interaction.	• Setup picture to show layout • Note one laptop, iOLab turned onto its wheels, battery operated car connected to iOLab, two students facing ensemble and camera held by F3, etc.	
In sequence below girl connects the sensor, the reference frame (printed axes), and the motion of the iOLab to what happens on graphs.						
1	**00:05**	F3	Yeah… so, so ..you mentioned the word reference.	▪ F3, standing, holds RH in front of his chest with index finger pointing forward. ▪ Both S14 &S13 sits watching F3 with	• Speech, body (gesture) • Purpose/Meaning – finger pointing seems to relate to the word	

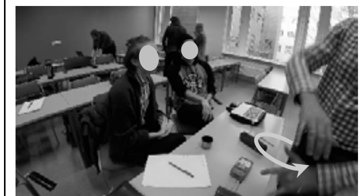
				arms folded in front of their chests.	"reference" / or perhaps the previous discussion.	
2	**00:08**	F3	Can you expand a bit, on that {g}? Uhm, what did you, is meant by the reference?	▪ {g}F3 holds his hands together in a closed fists but with open index finger position, and rolls his hands. ▪ S13&S14 keeps arms tightly folded, listening intently.	• Speech, hand gesture • Purpose/Meaning – rolling hands indicate embodiment of "expand" or 'unpack what you mean'	
3	**00:12**	S13	Well, I was thinking that{g}, its, the reference system, according to the, …(*trying to find right word*), look, according to the , {g} the <u>sensor</u>?{g}…	▪ {g}From folded arms, S13 first uses both arms in large circular motions; ▪ {g}then lifts arm and hand and forcefully pushes RH forward with index finger directed at the part of box with printed axes. ▪ {g} inverted commas gesture with both hands	• Speech, hand gesture • Purpose/Meaning – {g}: explanation gesture {g}: linking her verbal description of "reference system" to the printed axes as well as the word "sensor".	

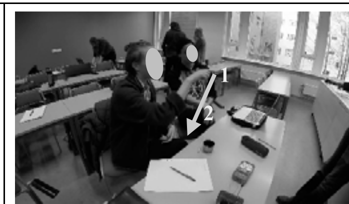
4	**00:21**	S13	And, … then it doesn't matter if you, like, … if you let the car go{g}this way,	▪ {g} Draws RH (with index finger pointing down) along imaginary line of travel along length of table from L→R	• Speech, body & gesture • Purpose/Meaning:- {g}: signifies the motion of the toy car with iOLab in tow along straight line on tabletop from L→R	
5	**00:27**	S13	{g} And then just turn the whole car around	▪ {g} Now makes a turning movement with her forearm and RH ▪	• Speech, gesture • Purpose/Meaning:- {g}: hand gesture and movement shows girl imagining holding the box in her hand and turning it around.	
6	**00:30**	S13	…{g} then you don't change the position of the sensor, in, … uh…{g},	▪ {g} points with RH with index finger at box again ▪ {g}RH with index finger now 1st points downward at axes, and then starting from a position next to the toy car, she gestures with pointing finger in opposite	• Speech, gesture • Purpose/Meaning:- {g}: points at what she is talking about (the sensor for her is represented by the axes) {g}: pointing finger backwards & forwards next to box signifies S13 trying to explain	

				direction to before (R→L, not L→R). ▪ [Note: the 2nd gesture immediately follows the first.]	motion relative to the sensor/axes, but now in opposite direction on table.	
7	**00:34**	S13	in …, mm, .. {g} how do you say it	▪ {g} clicks fingers of RH a couple of times.	• Speech, gesture • Purpose/Meaning:- {g}: trying to find word.	
8	**00:36**	F1	… In relation? In relation to …	▪	• Speech	
9	**00:38**	S13	Yeah, in relation to the car {g}	▪ {g} RH open palm directed at car.	• Speech, gesture • Purpose/Meaning:- {g}: talking about car … "in relation to…"	
10	**00:39**	S13	Then, it will just, like, [slight pause with RH held in position as before to explain motion of car in opposite direction]…it won't show on the graph {g}	▪ {s} LH open palm directed at PC screen	• Speech, gesture • Purpose/Meaning:- {s}: S13 now has taken the explanation, from first linking the sensor to the reference axis, then the motion of box in relation to the sensor/axes, to now linking these to	

					the outcome on the screen “won’t show on the graph”.	
11	**00:43**	S13	Erh, but if, you…, like eh, back the car {g}, backwards again, eh (smiling, [to seek approval of word or idea from F3]), in <u>opposite</u> [emphasis in a questioning sense] direction, …	▪ {g}RH hand now swept across table above apparatus from R to L across table.	• Speech, gesture • Purpose/Meaning:- {g}: depicting reversed motion of car in direction opposite to original direction but with axes still pointing in the original dir’n.	
12	**00:52**	S13	, …then it would show like on the graph, because {g}, …	▪ {s} RH now in open palm up gesture directed at screen.	• Speech, gesture • Purpose/Meaning:- {s}: again linking her embodied explanation of motion to graph output	
13	**00:54**	S13	…{g} then, {g}…	▪ {g}Hands in open palm-up positions ▪ {g} RH rest on table with index finger on box pointed at axes. Moves the box slightly to the left.	• Speech, gesture • Purpose/Meaning:- {g}: explaining {g}: linking her expalantion of graph back to the box, its motion and the axes.	

14	**00:55**	F3	OK, what is happening do you think, {g}; what do you think the graph will show?	▪ {g}S13 RH with finger still on box.	• F1 zooms in on hand on box with index finger pointing at axes.	
15		S14	If you, back, move it backwards?	▪ {g} S14 moves both hands in a backward motion gesture (from R to L – the way he's sitting)	• Speech, gesture • Purpose/Meaning:- {g}: embodied gesture to show and confirm which situation is being referred to by F3.	
16	**01:02**	S13	In which situation?	▪ {g} S13 puts out hand in open palm up gesture, and then folds her hands in front of her	• Speech, gesture • Purpose/Meaning: {g} questioning gesture	
17	**01:03**	F3	In other words {g}, if you, if you, you move this to the,{g} the iOLab that way, …	▪ {g}F3 with LH with index finger and pinky above iOLab box. Thumb held out pointing along −y-axis.	• Speech, gesture • Purpose/Meaning:- {g}: fingers frame box for being moved in next gesture, thumb. {g} similar gestures&movements as	

				▪ {g} Then moves it along table to students' R (iOLab +y-axis pointing now opposite to thumb)	S13, F3 explains what he means – he wants to know what graphs would look like for the iOLab in reverse (moving in –y).	
18	**01:07**	F3	And then instead of turning the iOLab around {g}, …	▪ {g} F3 makes large sweeping rotational gesture with both arms and hands with LH still held with index finger and pinky pointing aligned.	• Speech, gesture • Purpose/Meaning:- {g}: similar to S13 before – left hand aligned to axis, and gesture to show iOLab is **not** turned around but just moved in opposite direction	
19	**01:09**	F3	…you just kind of reverse it {g}.	▪ {g} F3 moves entire body from L→R (R→L for students), with outstretched hands in original positions (LH fingers).	{g}: motion and alignment of LH shows for students the correct situation (thumb point opposite to +y-axis and original direction of motion (L→R for students), i.e. signifying iOLab rolled in opposite direction, but axes the same, not turned round.	

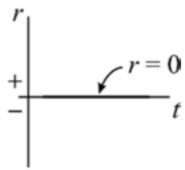
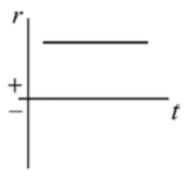
20	**01:11**	S13	Yah, then the graph {g} will go back to zero,…{g}	▪ {g}RH with index finger pointing at some focal point of vision. ▪ {g}embodied tracing of straight line with RH from aforementioned point in space down and to her R.	• Speech, gaze, gesture • Purpose/Meaning:- {g}: S13 seems to be referring to the point on *y-t* graph where the recording was stopped for original motion (iOLab moves in dir'n of +y) {g}: she is indicating how the r-t graph would look like, starting from the end of the first situation (iOLab in +y), and then correctly infers what the curve would look for reversing it (straight line back to starting position.	
21	**01:14**	S14	…Like, in the negative direction{g}	▪ {g} looks at S13 and gestures with RH down to his right {g}	• Speech, gaze, gesture • Purpose/Meaning:- {g}: to confirm S13's explanation	

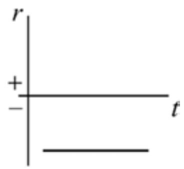
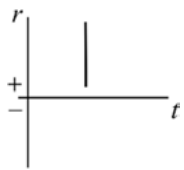
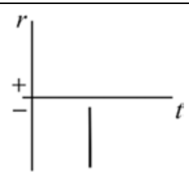
22	**01:17**	S13	I guess…[starts another hand gesture{g} but then stops …as F1 starts a probing question]	▪ {g}similar to first gesture in line 20.	• Speech, gesture • Purpose/Meaning:- {g}: Index finger and hand prepped for tracing a line	
23	**01:18**	F1	So, if it was rising first, then it would…{g}	▪ {g}S13 seem unsure how to explain further…F1 interjects and both students (esp. S13 stops explaining) now turns and listens.	• Speech, gesture • Purpose/Meaning:- {g}: S13 considering what F1 is saying with intense consideration.	
24	**01:19**	S13 (+S14 gesture)	Yeah, we would have like a constant, like a linear{g}, er .. graph [slight hesitation, stammering slightly];{g}the position where you turn back, then you would change {g} like this.	▪ {g}	• Speech, gesture • Purpose/Meaning:- {g}: S13 using hand and finger to trace out the imagined line that would be on the graph screen, from the “position where you turn back”.	

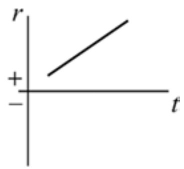
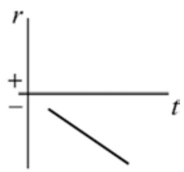
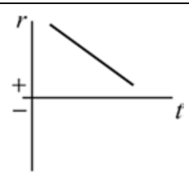
Appendix C

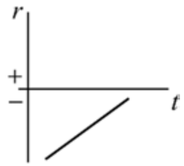
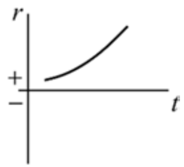
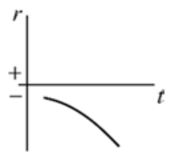
Appendix C
Semiotic audit of graph system for 1-D kinematics – graph shapes in the 1st and 4th quadrants

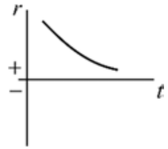
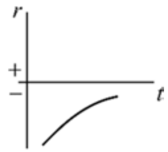
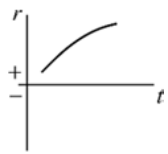
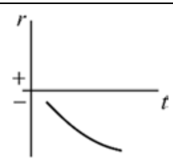
Table 6. *Semiotic relationships between the qualitative information contained in 1D-kinematic position-time graphs and (i) physics concepts, and (ii) real world motion descriptions thereof (16 shapes and $r = 0$).*

Graph Variable Relationships ***Position-time (r-t)***	Disciplinary descriptions /meanings and interpretations	
	(i) Physics Concept(s)	**(ii) Example of real world motion**
 1. Straight horizontal line, $r = 0$ (zero slope).	*Stationary* at the *reference point* of a reference axis [$r = 0$, $v = 0$, $a = 0$]	From the perspective of (as viewed by) a stationary observer, a car is *standing still*, idling at a traffic intersection (which happens to be where the 'zero' of an axis/ number line is placed).
 2. Straight horizontal line, $r > 0$ (zero slope).	*Stationary, positive position* [$r > 0$, $v = 0$, $a = 0$]	From the perspective of (as viewed by) a stationary observer, a car is *standing still* by the side of a straight road in the forward direction (other examples - right/east) from a traffic intersection (a chosen zero position).

 3. Straight horizontal line, $r < 0$ (zero slope).	*Stationary, negative position* [$r < 0$, $v = 0$, $a = 0$]	From the perspective (as viewed by) of a stationary observer, a car is *standing still* by the side of a road in the backward direction (other examples – left of /west) from a traffic intersection (a chosen zero position).
 4. Straight vertical line, $r > 0$ (slope is infinite).	*Instantaneous change in positive position* [$r > 0$, $v = \infty$, $a = \infty$]	Physically, this would mean a car being at all the positions at the same time instant—an impossibility. In reality, this line is an approximation for very sudden changes of position over extremely short time intervals.
 5. Straight vertical line, $r < 0$ (slope is infinite).	*Instantaneous change in negative position* [$r < 0$, $v = \infty$, $a = \infty$]	Similar to relationship 4.

 6. Straight line sloping up to right, $r > 0$.	*Constant positive velocity, positive position* $[r > 0, v > 0, a = 0]$	An object is moving on a straight path with *constant speed*, in the *positive direction* (e.g. to the right, forwards, East), *away* from the zero point. E.g. a car, *east* of a traffic intersection, is moving *eastwards* at a *constant speed* on a straight road.
 7. Straight line sloping down to right, $r < 0$.	*Constant negative velocity, negative position* $[r < 0, v < 0, a = 0]$	An object is moving on a straight path with *constant speed*, *opposite* to a defined positive direction (or in the *negative direction*, e.g. to the left, backwards, West), *away* from the zero point. E.g. a car, *west* of a traffic intersection, is moving *westwards* at a *constant speed* on a straight road.
 8. Straight line sloping down to right, $r > 0$.	*Constant negative velocity, positive position* $[r > 0, v < 0, a = 0]$	An object is moving on a straight path with *constant speed*, *opposite* to a defined positive direction (or in the *negative direction*), *towards* the zero point. E.g. a car, *east* of a traffic intersection, is moving *westwards* at a *constant speed* on a straight road.

 9. Straight line sloping up to right, $r < 0$.	*Constant positive velocity, negative position* [$r < 0$, $v > 0$, $a = 0$]	An object is moving on a straight path with *constant speed*, in a defined *positive direction*, *towards* the zero point. E.g. a car, *west* of a traffic intersection, is moving *eastwards* at a *constant speed* on a straight road.
 10. Curve up, more steep to right, $r > 0$.	*Positive acceleration with positive velocity, positive position* [$r > 0$, $v > 0$, $a > 0$] [Note: If the curve is known to be *parabolic*, the particle is described as undergoing a *constant* acceleration.]	An object is moving on a straight path with a *faster* and faster speed, in a defined *positive direction*, away from the zero point. E.g. a car, *east* of a traffic intersection, moves *eastwards* and *speeds up*.
 11. Curve down, more steep to right, $r < 0$.	*Negative acceleration with negative velocity, negative position* [$r < 0$, $v < 0$, $a < 0$] [See note in row 10.]	An object is moving on a straight path with a *faster* and faster speed, *opposite* to a defined positive direction (or in the *negative direction*), *away from* the zero point. E.g. a car, *west* of a traffic intersection, moves *westwards* and *speeds up*.

 12. Curve up, more gradual to right, $r > 0$.	*Positive acceleration with negative velocity, positive position* [$r > 0$, $v < 0$, $a > 0$] [See note in row 10.]	An object is moving on a straight path with a *slower* and slower speed, *opposite* to a defined positive direction (or in the *negative direction*), *towards* the zero point. E.g. a car, *east* of a traffic intersection, moves *westwards* and *slows down*.
 13. Curve down, more gradual to right, $r < 0$.	*Negative acceleration with positive velocity, negative position* [$r < 0$, $v > 0$, $a < 0$] [See note in row 10.]	An object is moving on a straight path with a *slower* and slower speed, in a defined positive direction, *towards* the zero point. E.g. a car, *west* of a traffic intersection, moves *eastwards* and *slows down.*
 14. Curve down, more gradual to right, $r > 0$.	*Negative acceleration with positive velocity, positive position* [$r > 0$, $v > 0$, $a < 0$] [See note in row 10.]	An object is moving on a straight path with a *slower* and slower speed, in a defined positive direction, *away* from the zero point. E.g. a car, *east* of a traffic intersection, moves *eastwards* and *slows down.*
 15. Curve up, more gradual to right, $r < 0$.	*Positive acceleration with negative velocity, negative position*: [$r < 0$, $v < 0$, $a > 0$] [See note in row 10.]	An object is moving on a straight path with a *slower* and slower speed *opposite* to a defined positive direction (or in the *negative direction*), *away* from the zero point. E.g. a car, *west* of a traffic intersection, moves *westwards* and *slows down.*

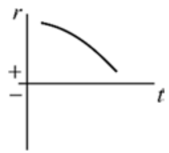
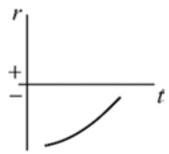
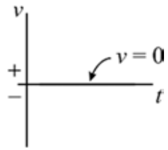
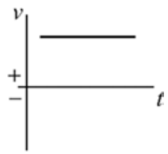
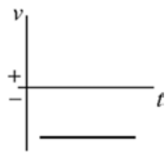
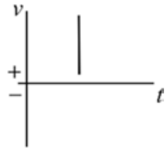
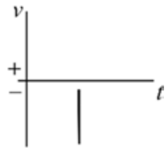
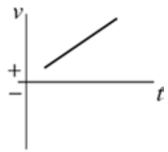
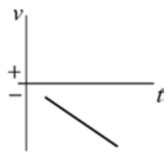
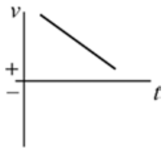
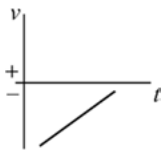
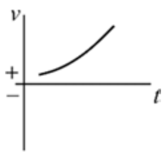
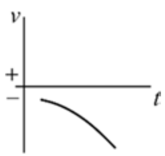
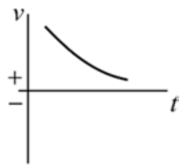
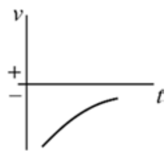
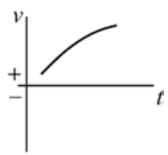
 16. Curve down, more steep to right, $r > 0$.	*Negative acceleration with negative velocity, positive position:* [$r > 0$, $v < 0$, $a < 0$] [See note in row 10.]	An object, moving on a straight path in a defined *positive direction* (e.g. East), is observed moving *faster* and faster *towards* the zero point, traversing larger distances in successive equal time intervals. E.g. a car, *west* of a traffic intersection, moves *eastwards* and *speeds up*.
 17. Curve up, more steep to right, $r < 0$.	*Positive acceleration with positive velocity, negative position*: [$r < 0$, $v > 0$, $a > 0$] [See note in row 10.]	An object is moving on a straight path with a *faster* and faster speed, in a defined *positive direction*, towards the zero point. E.g. a car, *west* of a traffic intersection, moves *eastwards* and *speeds up*.

Table 1. *Semiotic relationships between the qualitative information contained in 1d-kinematic velocity-time graphs and (i) physics concepts, and (ii) real world motion descriptions thereof (16 shapes & v =0).*

Graph Variable Relationships ***Velocity-time (v-t)***	**Disciplinary descriptions /meanings**	
	(i) Physics Concept(s)	**(ii) Example of real world motion**
 1. Straight horizontal line, $v = 0$ (zero slope).	*Zero velocity* i.e. *stationary* [Zero displacement over time in an *inertial reference frame.*] [$v = 0$, $a = 0$]	A rocket is *standing still (motionless)*, on a launch pad.
 2. Straight horizontal line, $v > 0$ (zero slope)	C*onstant / uniform motion – a constant velocity in positive direction* [$v > 0$, $a = 0$]	A rocket is moving vertically straight upwards at a constant speed, traversing equal distances in equal time intervals. Vertically up relative to the Earth is chosen as the positive reference axis.
 3. Straight horizontal line, $v < 0$ (zero slope).	C*onstant / uniform motion - a constant negative velocity* [$v < 0$, $a = 0$]	A parachute is deployed after a rocket has been fired and it falls to the ground vertically straight down at a constant speed, traversing equal distances in equal time intervals. Vertically up relative to the Earth is positive.

 4. Straight vertical line, $v > 0$ (slope is infinite).	*Instantaneous change in positive velocity* [$v > 0$, $a = \infty$]	See similar description in table 1 – r-t graphs.
 5. Straight vertical line, $v < 0$ (slope is infinite).	*Instantaneous change in negative velocity* [$v < 0$, $a = \infty$]	See similar description in table 1 – r-t graphs.
 6. Straight line sloping up to right, $v > 0$.	*Constant / uniform acceleration, positive velocity* [$v > 0$, $a > 0$]	A rocket fires its thrusters and moves straight upwards at a *constantly increasing speed*, traversing greater distances in successive equal time intervals. Vertically up relative to the Earth is positive.
 7. Straight line sloping down to right, $v < 0$.	*Constant / uniform negative acceleration, negative velocity* [$v < 0$, $a < 0$]	A rocket is falling to earth straight downwards at a *constantly increasing speed*, traversing greater distances in successive equal time intervals. Vertically up relative to the Earth is positive.

 8. Straight line sloping down to right, $v > 0$.	*Constant / uniform negative acceleration, positive velocity* [$v > 0$, $a < 0$]	A rocket stops firing its thrusters and now moves straight upwards at a *constantly decreasing speed*, traversing smaller distances in successive equal time intervals. Vertically up relative to the Earth is positive.
 9. Straight line sloping up to right, $v < 0$.	*Constant /uniform positive acceleration, negative velocity* [$v < 0$, $a > 0$]	A rocket falling to Earth vertically straight down, fires its retro-thrusters and moves at a *constantly decreasing speed*, traversing smaller distances in successive equal time intervals. Vertically up relative to the Earth is positive.
 10. Curve up, more steep to right, $v > 0$.	*Positive jerk, positive acceleration, positive velocity* [$v > 0$, $a > 0$, $j > 0$] [Note: the rate of change of acceleration, or *jerk (j),* is *constant* or uniform if curve is *parabolic*.]	A rocket is fired straight upwards with increasing thrust moving at an ever increasing rate of speed, i.e. the rate of increase of upward speed (upward acceleration) is also increasing. Vertically up relative to the Earth is positive.
 11. Curve down, more steep to right, $v < 0$.	*Negative jerk, negative acceleration, negative velocity* [$v < 0$, $a < 0$, $j < 0$] [See note in row 10.]	A rocket is diving to Earth vertically straight down, fires its thrusters, and moves downwards at an ever increasing rate of speed, i.e. the rate of increase of downward speed is also increasing. Vertically up relative to the Earth is positive.

 12. Curve up, more gradual to right, $v > 0$.	*Positive jerk, negative acceleration, positive velocity* [$v > 0$, $a < 0$, $j > 0$] [See note in row 10.]	A rocket moving upwards (chosen reference axis is vertically up) fires its retro-thrusters, gradually and continuously reducing reverse thrust, resulting in the rocket slowing down ever more gently.
 13. Curve down, more gradual to right, $v < 0$.	*Negative jerk, positive acceleration, negative velocity* [$v < 0$, $a > 0$, $j < 0$] [See note in row 10.]	A rocket in a controlled fall straight down (vertically up is positive), fires its thrusters (pointing down), gradually and continuously reducing thrust, resulting in the rocket slowing down ever more gently.
 14. Curve down, more gradual to right, $v > 0$.	*Negative jerk, positive acceleration, positive velocity* [$v > 0$, $a > 0$, $j < 0$] [See note in row 10.]	A rocket is fired straight upwards increasing its speed. The rate of increase of upward speed is decreasing as the thrusters are gradually turned down. The reference axis is vertically up.

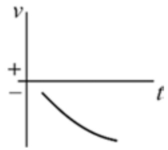
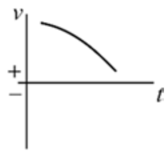
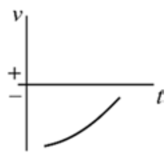
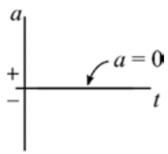
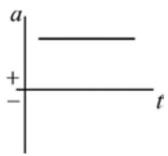
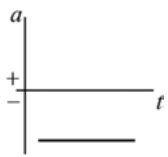
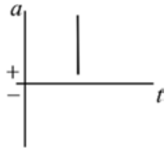
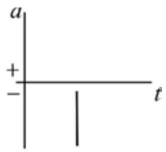
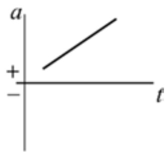
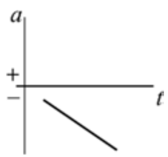
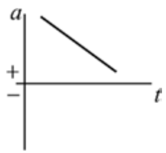
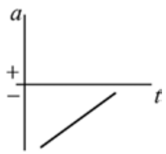
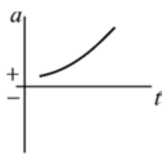
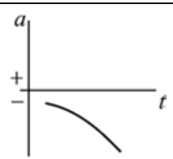
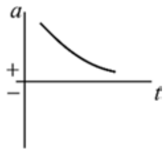
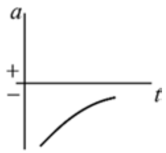
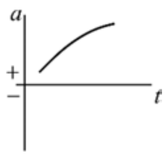
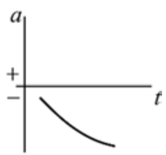
 15. Curve up, more gradual to right, $v < 0$.	*Positive jerk, negative acceleration, negative velocity* [$v < 0$, $a < 0$, $j > 0$] [See note in row 10.]	A rocket is fired straight upwards increasing its speed. The rate of increase of upward speed is decreasing as the thrusters are gradually turned down. The reference axis is vertically down. OR A rocket in a dive straight down (vertically up is positive), gradually and continuously decreases thrust, resulting in the rocket speeding up at an ever more gradual rate.
 16. Curve down, more steep to right, $v > 0$.	*Negative jerk, negative acceleration, positive velocity* [$v > 0$, $a < 0$, $j < 0$] [See note in row 10.]	A rocket moving upwards (chosen reference axis is up) fires its retro-rockets, gradually and continuously increasing reverse thrust, resulting in the rocket slowing down at an ever increasing rate.
 17. Curve up, more steep to right, $v < 0$.	*Positive jerk, positive acceleration, negative velocity* [$v < 0$, $a > 0$, $j > 0$] [See note in row 10.]	A rocket moving upwards (chosen reference axis is down) fires its retro-rockets, gradually and continuously increasing reverse thrust, resulting in the rocket slowing down at an ever increasing rate. OR A rocket in a controlled fall, gradually and continuously increases its upward thrust (vertically up is positive), resulting in the rocket slowing down at an ever increasing rate.

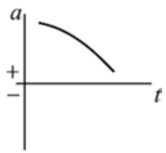
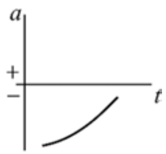
Table 8. *Semiotic relationships between the qualitative information contained in 1d-kinematic acceleration-time graphs and (i) physics concepts, and (ii) real world motion descriptions thereof (16 shapes & a = 0)*

Graph Variable Relationships ***acceleration-time (a-t)***	**Disciplinary descriptions /meanings**	
	(i) Physics Concept(s)	**(ii) Example of real world motion**
 1. Straight horizontal line (zero slope) at $a = 0$	*Zero acceleration* i.e. *constant / uniform motion (velocity)* [No change in velocity over time in an *inertial reference frame.*] [$a = 0, j = 0$]	On a straight road, a car is either; a. standing still (i.e. not moving), or, b. moving along a chosen axis at constant speed, or c. moving opposite to the chosen positive axis at constant speed. [Note that these correspond to relationships 1, 2 and 3 for *v-t.*, and 1, 2, 3, 6, 7, 8, or 9 for *r-t*] Also
 2. Straight horizontal line (zero slope), $a > 0$	C*onstant / uniform positive acceleration* [Note: the velocity is changing in the positive direction.] [$a > 0, j = 0$]	On a straight road, a car is either; a. see description for relationship 6, *v-t*, or, b. see description for relationship 9, *v-t*.
 3. Straight horizontal line (zero slope), $a < 0$	C*onstant / uniform negative acceleration* [Note: the velocity is changing in the negative direction.] [$a < 0, j = 0$]	On a straight road, a car is either; a. see description for relationship 7, *v-t*, or, b. see description for relationship 8, *v-t*

 4. Straight vertical line (slope is infinite), $a > 0$	*Instantaneous change in positive acceleration* $[a > 0, j = \infty]$	See similar description in table 1 – r-t graphs. Additional note: This kind of shape is much more common for acceleration time as there are many situations where acceleration changes abruptly, e.g. a change of direction at the top of an incline for a car rolling up and then down a hill.
 5. Straight vertical line (slope is infinite), $a < 0$	*Instantaneous change in negative acceleration* $[a < 0, j = \infty]$	See description in 4 above.
 6. Straight line sloping up to right, $a > 0$	*Constant / uniform positive jerk, positive acceleration* (magnitude of acceleration in positive direction is increasing uniformly) $[a > 0, j > 0]$	See descriptions for either; a. *v-t* relationship 10 (column 3), or, b. *v-t* relationship 17 (column 3). [Note: from this point to curve 17, although not common, students are expected to know qualitatively the implications of these curves, as well as be able to deduce changes in velocity, etc.]
 7. Straight line sloping down to right, $a < 0$	*Constant negative jerk, negative acceleration* (magnitude of acceleration in negative direction is increasing uniformly) $[a < 0, j < 0]$	See descriptions for either; a. *v-t* relationship 11 (column 3), or, b. *v-t* relationship 16 (column 3).

 8. Straight line sloping down to right, $a > 0$	*Constant negative jerk, positive acceleration* (magnitude of acceleration in positive direction is decreasing uniformly) [$a > 0, j < 0$]	See descriptions for either; a. *v-t* relationship 13 (column 3), or, b. *v-t* relationship 14 (column 3).
 9. Straight line sloping up to right, $a < 0$	*Constant positive jerk, negative acceleration* (magnitude of acceleration in negative direction is decreasing uniformly) [$a < 0, j > 0$]	See descriptions for either; a. *v-t* relationship 12 (column 3), or, b. *v-t* relationship 15 (column 3).
 10. Curve up, more steep to right, $a > 0$	*Positive snap, positive jerk, positive acceleration* [$a > 0, j > 0, s > 0$] [Note: *snap (s) is constant* or *uniform* if curve parabolic]	From here on real world examples are not obvious or easy. Examples would entail non-linear ‘impulsive’ forces, e.g. accelerations experienced by baseballs while in contact with a bat, hitting an object with short jabs, bouncing balls off walls, etc.
 11. Curve down, more steep to right, $a < 0$	*Negative snap, negative jerk, negative acceleration* [$a < 0, j < 0, s < 0$] [see Note in row 10.]	See row 10.

 12. Curve up, more gradual to right, $a > 0$	*Positive snap, negative jerk, positive acceleration* [$a > 0, j < 0$, s > 0] [see Note in row 10.]	See row 10.
 13. Curve down, more gradual to right, $a < 0$	*Negative snap, positive jerk, negative acceleration* [$a < 0, j > 0$, s < 0] [see Note in row 10.]	See row 10.
 14. Curve down, more gradual to right, $a > 0$	*Negative snap, positive jerk, positive acceleration* [$a > 0, j > 0$, s < 0] [see Note in row 10.]	See row 10.
 15. Curve up, more gradual to right, $a < 0$	*Positive snap, negative jerk, negative acceleration* [$a < 0, j < 0$, s > 0] [see Note in row 10.]	See row 10.

 16. Curve down, more steep to right, $a > 0$	*Negative snap, negative jerk, positive acceleration* [$a > 0, j < 0$, s < 0] [see Note in row 10.]	See row 10.
 17. Curve up, more steep to right, $a < 0$	*Positive snap, positive jerk, negative acceleration* [$a < 0, j > 0$, s > 0] [see Note in row 10.]	See row 10.

Appendix D

Appendix D

Examples of task instruction sheets

Magnetometer activity instruction sheet (English)

Wheel sensor activity

D1. Magnetometer activity instruction sheet (English)

Uppsala University / XXX Gymnasiet Na14

Exercise with earth's magnetic field

Preparation: Drivers and IOLab program can be downloaded from www.iolab.science. Follow instructions on how to install driver. Unzip IOLab-program at a convenient location in your computer.

Calibration: this step is essential to make sure that you get as true measurements as possible.
1st step: Place the IOLab on the white plastic box. This is to ensure that the IOLab is far away from the influence of iron during calibration. Plug in the USB-dongle in your computer and start the IOLab then start the IOLab program. Click on the cogwheel and work your way through the calibration of accelerometer magnetometer and gyroscope. Be sure to place the IOLab as shown in the pictures while going through the calibration steps. The view in the pictures are from the side, not from above!

Measurements and goal: With the IOLab you can test different sensors and perform many experiments. This time we concentrate on the magnetic field. To make the IOLab measure magnetic field you must tick the magnetometer box in the Sensors list and click Record.
The task is to measure the direction of the earth magnetic field at different locations and to fix an arrow that represent the direction of the magnetic field in the class room. Together we will produce a nice view of the earth's magnetic field in the room.

Extra tasks could be measure the field strength as a function of distance from a magnet, try to find where the reinforcement are located in the floor or something else.

D2. Wheel sensor activity

Task statements to students – no instruction sheet given

The tasks were presented verbally and summarized on the blackboard.

Task 1 – Observe motion and the shapes and link these to the kinematics concept

a. Connect the toy car to the IOLab-box.
b. Observe its motion and the graphs *(position-versus-time*, *velocity-time* and *acceleration-time*) on the computer screen. What can you say about the motion? Think about the features of the graphs.
c. If you turn the whole setup around (moving in opposite direction), what would you expect the graphs to show? Try it and see.
d. If you turn the IOLab box around (front end facing backward), and the toy car moves in the same direction, what would you expect the graphs to look like now? Can you explain this?

Task 2 – linking motion to kinematics concept of constant acceleration, predict and explain the graphs

a. Design an experiment for which the IOLab-box will move with a constant acceleration.
b. How can you be sure that the IOLab-box is in fact moving with a constant non-zero acceleration?
c. What happens if you turn the box around (front to back) and move it in the same direction as before?

Task 3 – reproduce the "double bumps" (+/−) – interpret kinematic meaning of graph shapes and produce the motion

Your task is to reproduce, by performing experiments with your hands and the IOLab-box, the "double-bump" curves drawn on the blackboard. Try not to rely on ramps or other devices for this task. Use only your hands, unless you can only achieve the features you want by using your artefacts or extra apparatus.

Appendix E

Appendix E

Example of an informed consent information sheet
Example of an ethical consent form
Redacted HSSREC application document

E1. Example of an informed consent information sheet

UPPSALA UNIVERSITY PER *Informed consent – Information Sheet* UPPSALA UNIVERSITET

A social semiotic approach to the use of mathematical tools in the teaching and learning of physics

PARTICIPANT INFORMATION SHEET

You are being invited to take part in research on the teaching and learning of physics, i.e. physics education research.

Trevor Volkwyn, a full time PhD student in the Division for Physics Education Research at Uppsala University, is leading this research.

Before you decide to take part, it is important you understand why the research is being conducted and what it will involve. Please take time to read the following information carefully.

What is the purpose of the study?

This study will explore how students engage with each other, their teachers, work with educational laboratory design, and mathematical tools and resources, in open-ended, active engagement learning settings.

Why have I been chosen to take part?

You are invited to participate in this study because you are currently enrolled in an introductory course in physics.

What are the benefits of taking part?

By participating, you will be assisting the research staff of the Uppsala University Physics Education Research Group in making a contribution to research that aims at obtaining a better understanding of how to provide physics students with better access to abstract mathematical and physics ideas.

Are there any risks associated with taking part?

There are no specific risks associated with participation.

Do I have to take part?

No – it is entirely up to you. If you do decide to take part, please keep this Information Sheet and complete the Informed Consent Form to show that you understand your rights in relation to the research, and that you are happy to participate.

You are free to withdraw your information from the study at any time up until the data are completely anonymized. If you withdraw, your raw data will be destroyed. Please refer to the section "Data Protection and Confidentiality" below for further details.

It is important to note that your anonymized data may be used in the production of formal research outputs, such as journal articles, conference presentations and papers, theses and research reports.

You are therefore advised to contact the lead researcher at the earliest opportunity should you wish to withdraw from the study.

To withdraw, please contact the lead researcher (contact details are provided below). In the event of the lead researcher's absence please contact either John Airey (john.airey@physics.uu.se) or Cedric Linder (cedric.linder@physics.uu.se) so that your request can be dealt with promptly.

You do not need to give a reason. A decision to withdraw, or not to take part, will not affect you in any way.

What will happen if I decide to take part?

You will take part in an open-ended active engagement activity which will take place during one of your scheduled class periods. You will not be required to spend any extra time on the activity outside of the scheduled time slot.

If you decide to participate, you should choose a working partner who has also agreed to participate in the research, since we will study your pair work when scrutinising the data. In addition, we request that you agree to communicate in English. The activity will involve working with educational laboratory design.

Even though the activity forms part of your planned curriculum, the collected data will not affect your grade in any way.

In the said activity we will collect video and audio data of your engagement with each other, the teacher, any other researchers and the set of resources made available to you (e.g. mathematics, a device system called the IOLab, and a laptop). This, together with researcher field notes and any written work you may produce during the activity, will make up the research data.

Prior to the activity, we will ask you to download and install the IOLab system operating software onto your laptops.

Please note that since the data includes video, you could be identified in the data until it gets completely anonymized. Thus, you have the right to have video data that includes your face excluded from the study.

Data Protection and Confidentiality

If you consent to participate in this study, your data will be processed in accordance with the General Data Protection Regulation (GDPR) (EU) 2016/679. All information collected about you will be kept strictly confidential. If you consent to being video recorded, all recordings will be treated anonymously—not linked to your personal information e.g. name and contact details. Furthermore, all the raw data will be destroyed after the quality of the research has been established. This process will be officially checked on a regular basis.

For more information about how Uppsala University handles personal data, please follow the link, https://www.uu.se/en/about-uu/data-protection-policy/.

Your personal contact information will only be used to contact you in the event that there are changes to the agreement and consent you have given us as stipulated in the consent form.

Your data will only be viewed and accessed by the Uppsala University Physics Education Research group research team and colleagues.

All electronic data will be stored on password-protected computers or two offline hard drives, which together with all paper records, will be stored in locked filing cabinets in a lockable office at Ångströmlaboratoriet, Uppsala University. Only temporarily, your data may be stored on a university approved, secure, digital facility for the purposes of analysis and sharing it amongst the researchers in the study.

Your consent information will be kept separately from your responses (video data and/or written work) in order to minimise risk in the event of a data breach. The lead researcher will take responsibility for data protection as per the above.

What will happen with the results of this study?

As described earlier, the results of this study may be summarised in published articles, reports and presentations. However, anonymity is guaranteed by, for example, using sketches, fully anonymous transcriptions, and masking of audio and video clips—making it impossible to identify you in any way.

Making a Complaint

If you are unhappy with any aspect of this research, please first contact the lead researcher, Trevor Volkwyn (contact details provided below).

After this, if you still have concerns about your participation in this study, you should put them in writing to:

Cedric Linder
Programme Responsible Professor
Division of Physics Education Research, Uppsala University
Email: [redacted]@[redacted]

In your letter please provide information about the research project, specify the name of the researcher and detail the nature of your complaint.

What rights do I have?

You have the right to access information held about you. Your right of access can be exercised in accordance with the General Data Protection Regulation (GDPR) (EU) 2016/679. You also have other rights including rights of correction, erasure, objection, and data portability. Please see https://www.datainspektionen.se/other-lang/in-english/the-general-data-protection-regulation-gdpr/the-data-subjects-rights/.

Uppsala University is the legal Data Controller for the information you provide. If you have more general questions about the controller of personal data and the processing of personal data at Uppsala University, or if you wish to exercise any of your rights listed above, you may contact Uppsala University (address details at http://www.uu.se/en/about-uu/contact/) and the data protection officer through email at dataskyddsombud@uu.se.

Anyone who believes that Uppsala University has processed his or her personal data contrary to the GDPR and related supplementary national legislation has the right to submit complaints to the Swedish Data Inspection Board (http://www.datainspektionen.se, and email datainspektionen@datainspektionen.se).

Contact Information of lead researcher

Trevor S. Volkwyn
PhD student
Division of Physics Education Research, Uppsala University
Email: trevor.volkwyn@physics.uu.se
Mobile: [redacted]
Office: [redacted]

E2. Example of an ethical consent form

Deltagande i en vetenskaplig studie om hur tekniska hjälpmedel påverkar elevers lärande av fysik.

Vi är forskare på avdelningen Fysikens Didaktik, institutionen för Fysik och Astronomi, Uppsala universitet(Bor Bregorčič, Filip Heijkenskjöld, Trevor Volkwyn) . Vi vill förbättra undervisningen i fysik genom att använda några tekniska hjälpmedel (t.ex. IOLab och Algodoo) och undersöka hur det påverkar elevers lärande. Vi hoppas på din hjälp för att öka vår förståelse och bidra till en forskningsbaserad pedagogisk utveckling. Allt deltagande i undersökningen är frivillig. Du kan när som helst under studien välja att hoppa av, men i sådana fall behåller vi data som redan har samlats in.

Data som samlats in genom att videofilma spela in ljud eller anteckningar kommer att analyseras genom att t.ex. skriva ut och tolka vad ni säger och gör. Analyserna kan komma att presenteras på konferenser och i vetenskapliga artiklar, men inte i andra sammanhang. För att garantera din anonymitet kommer inte ditt eller din skolas namn att publiceras. Videomaterial kommer inte att publiceras t.ex. i sociala media eller YouTube. I rapportering av resultat kommer alla svar att vara anonymiserade. Undersökningen genomförs i enlighet med god forskningssed.

Information om tekniska hjälpmedlen, http://iolab.science/ http://www.algodoo.com/ och

om god forskningssed, http://codex.vr.se/manniska1.shtml http://codex.vr.se/manniska2.shtml

Medgivande

Härmed godkänner jag att min medverkan i intervjuer och videoinspelning används i forskning och analysarbete av forskare vid Fysikens Didaktik, Uppsala universitet.

	Elevs godkännand	Målsmans godkännande för omyndig elev
Ort och datum	___________________	___________________
Namnteckning	___________________	___________________
Förtydligande	___________________	___________________

E3. Redacted HSSREC application document

[redacted]

ETHICAL CLEARANCE APPLICATION FORM (HUMANITIES AND SOCIAL SCIENCES RESEARCH ETHICS COMMITTEE)

PLEASE NOTE THAT THE FORM MUST BE COMPLETED IN TYPED SCRIPT. HANDWRITTEN APPLICATIONS WILL NOT BE CONSIDERED

SECTION 1: PERSONAL DETAILS

1.1 Surname of Applicant : Volkwyn
1.2 First names of applicant: Trevor Stanton
1.3 Title (Ms/ Mr/ Mrs/ Dr/ Professor etc) : Mr

1.4 Applicant's gender : Male
1.5 Applicant's Race (African/ Coloured/Indian/White/Other) : Coloured (self-classification of race required by South African legislation)
1.6 Student Number (where applicable) :
Staff Number (where applicable) : [redacted]
1.7 School : ________________________________
1.8 College : ________________________________

1.9 Campus : [redacted] main campus - Physics

1.10 Existing Qualifications : M.Sc.

1.11 Proposed Qualification for Project : Ph.D.
(In the case of research for degree purposes)

2. Contact Details
Tel. No. : 021 705 95 51 (SA); +46 18 471 35 57 (Sweden)
Cell. No. : 081 340 41 28 (SA); +46 79 337 71 03 (Sweden)
e-mail : tvolkwyn@uwc.ac.za / trevor.volkwyn@physics.uu.se
Postal address (in the case of Students and external applicants) : Staff member (& PhD student, Uppsala Univ., Sweden)

3. SUPERVISOR/ PROJECT LEADER DETAILS

NAME	TELEPHONE NO.	EMAIL	SCHOOL / INSTITUTION	QUALIFICATIONS
3.1 Dr John Airey (Reader ≡ Assoc. Prof.)	+46 18 471 35 73	john.airey@physics.uu.se	Uppsala Univ., Sweden	PhD
3.2 Prof. Cedric Linder	+46 18 471 35 39	cedric.linder@physics.uu.se	[redacted]/ Uppsala Univ., Sweden	PhD

SECTION 2: PROJECT DESCRIPTION

Please do *not* provide your full research proposal here: what is required is a short project description of not more than two pages that gives, under the following headings, a brief overview spelling out the background to the study, the key questions to be addressed, the participants (or subjects) and research site, including a full description of the sample, and the research approach/ methods

2.1 Project title
A study of the didactic and pedagogical relations between physics and mathematics in physics education

2.2 Location of the study (where will the study be conducted)
[redacted] (Physics Department) with comparative study in Sweden (local science upper secondary school – [redacted] gymnasiet)

2.3 Objectives of and need for the study
(Set out the major objectives and the theoretical approach of the research, indicating briefly, why you believe the study is needed.)

Recent PER work has begun to produce compelling evidence that many physics students lack essential parts of mathematics conceptual understanding, which results in severely limiting the possibility of working appropriately and/or productively with problem solving, and/or effect further advanced learning in a range of negative ways (e.g., Christensen & Thompson, 2012). Of interest from a contextually relevant perspective, is the dire state of mathematics education at upper secondary and introductory university levels in South Africa, and how this situation is most likely having a negative effect on physics teaching and learning. As an Extended Curriculum Programme (ECP) specialist at the [redacted] I have first-hand experience and perspective on this situation, observing with concern the deteriorating proficiency in mathematics of university entrants in the sciences and engineering. The broad objectives are to embark on a series of studies that explore the teaching and learning relations between mathematical knowledge and constructing appropriate ways of understanding and applying physics. The theoretical framing will build on the work of Airey & Linder (2009), who argued that in undergraduate physics there is a *critical constellation* of semiotic resources that are needed in order to make appropriate learning possible. By semiotic resources is meant language, graphs, diagrams, laboratory work, apparatus, mathematics, etc. Duval (2006) argues that whilst many teachers focus on teaching mathematical operations (what he calls treatment), the main problem occurs in the movement between one semiotic system and another (what he terms conversion). This movement between the various modes of representing a discipline is termed as *transduction* by Gunther Kress (1997). A number of researchers have identified this movement as critical for the ability to do physics (e.g. Lemke, 1998; Van Heuvelen, 1991; Mc Dermott 1990). In this respect, Fredlund, Airey & Linder (2012) introduced the term *disciplinary affordance* to denote the role played by an individual semiotic resource in the discipline of physics. Taking this idea further, Airey (2015) defines *pedagogical affordance* as “the aptness of a semiotic resource for the teaching and learning of some particular educational content”. In this study the relationship between the disciplinary and pedagogical affordances of mathematical semiotic resources used in undergraduate physics will be examined. This (inverse) relationship suggests that the most efficient way to learn physics may not be simply by using disciplinary resources with high disciplinary affordance (i.e. by doing physics) but rather by using other semiotic resources with high pedagogical affordance, that better give students access to physics concepts. This study will investigate the teaching and learning relations between semiotic resources in mathematics and physics, as well as investigating how newly available pedagogical tools like the IOLab (a handheld laboratory device that allows real time data collection and presentation) can assist the transduction between students’ and disciplinary semiotic resources, and how this affects meaning making and learning in physics.

2.4 Questions to be answered in the research
(Set out the critical questions which you intend to answer by undertaking this research.)

The structure of this PhD study (typical in Sweden) involves extensive coursework, especially during the first year of study, during which more detailed research questions will be developed. The first year of study (September 2016 – August 2017) therefore will focus on the exploration of relations between disciplinary, pedagogical semiotic resources and student learning outcomes. Initially, my personal focus is in the area of coordinate systems at the introductory physics education level. This will involve exploratory data being collected both in Sweden and possibly in South Africa ([redacted]). This data and new knowledge gained from coursework and literature reading will help me formulate, write and present a full research proposal in Feb-March 2017. I therefore present only a preliminary set of research questions here, formulated around the exploratory work into probing the links between mathematical and physics semiotic resources in the learning of disciplinary aspects of physics (coordinate systems).

2.4.1. How can the key disciplinary relevant aspects of coordinate systems be made noticeable to students in order for them to appreciate the disciplinary affordances of the system of semiotic resources as used in the discourse of physics?

2.4.2. How available and effective are the semiotic resources in physics to help students cultivate disciplinary fluency and appreciation of the disciplinary relevant aspects of coordinate systems?

2.4.3. Does the IOLab contribute in giving students access to the disciplinary relevant aspects of coordinate systems, and in which ways does it stimulate appreciation of the disciplinary affordances of the system of semiotic resources employed when working with coordinate systems?

2.4.4. Can students' everyday semiotic resources familiar to them be leveraged to mediate fluency in and appreciate the meaning potentials of physics semiotic resources (e.g. in the area of coordinate systems), i.e. to have a holistic experience of the disciplinary way of knowing?

2.4.5. Which semiotic resources available for unpacking coordinate systems are particularly problematic for students and how may this be addressed?

The investigation around these preliminary questions will feed into developing the theoretical framework which will crystallize and refine the research questions.

2.5 Research approach/ methods
(This section should explain how you will go about answering the critical questions which you have identified under 2.4 above. Set out the approach within which you will work, and indicate in step-by-step point form the methods you will use in this research in order to answer the critical questions – including sample description, sampling strategies, data collection methods, and data reduction strategies.

For a study that involves surveys, please append a provisional copy of the questionnaire to be used. The questionnaire should show how informed consent is to be achieved, as well as indicate to respondents that they may withdraw their participation at any time, should they so wish.

For the exploratory study, data will be collected of students working in a laboratory setting using PC's and laptops engaging with the IOLab device. In some instances, a guided response worksheet with mostly open ended questions will be provided, and in other activities just an instruction sheet with a clearly defined task and goal statement. Video and interview data will be collected of students working with experimental design (IOLab) that potentially encourages transduction, with comparative data collection in Sweden and South Africa. The protocol before commencement of the activities involves students receiving a consent form, explanation of the voluntary nature of the study and students signing the consent form. Students will be given copies of the signed forms, on which are the contact details of the principal investigator in the case that a student wants to withdraw from the study for whatever reason. A copy of the consent form is attached.

The study *may* involve a survey questionnaire, which will be developed after the first phase of the data collection, i.e. the exploratory study mentioned in 2.4 and above. It is therefore not available at this stage, as the information needed to compile this will be gathered in phase 1.

The student samples involved in the first phase are (i) a group of upper secondary ("gymnasiet") school students in Uppsala, Sweden – representing high achieving science students who will very likely pursue science degree at university, and (ii) ECP (extended curriculum programme) students in their first and second years of study (first year level) – representing students with potential but having had not the same level of science education at school as compared with Swedish learners. The rationale behind this choice of groups for possible comparison is that although different in age (1-3 years), they could be at the same level in terms of disciplinary knowledge about physics. However, the main reason is that the groups represent opposite extremes in terms of school preparation and availability of resources, and it is thus envisaged that the study will make interesting findings about the similarities and differences between these cohorts, which could enlighten the researchers on the links between different mathematical and physics semiotic resources and the interplay between disciplinary and pedagogical affordances, especially in relation to different learning backgrounds. This is important from a pedagogical point of view informed by our theoretical basis – what modes are critical and how are these (or how should they be) made available to students, in order for students to have a more holistic experience of the facets of the disciplinary ways of knowing that the mode/s give access to?

The video data will be transcribed to identify links between resources employed by students, those available in the discipline, and when or whether transduction occurs in different learning moments. The data analysis technique is therefore qualitative and participant responses and gestures (students and learning facilitator who is also a researcher and may or may not be the main investigator) will be used to develop the affordance links within the theoretical framework set out above. The data will be used to attempt to answer the preliminary research questions set out in section 2.4. This information will then inform the *possible* development of a questionnaire (as mentioned before) in the second or third year of study to test students' fluency of use within the critical constellation of semiotic resources necessary for gaining access to a disciplinary way of knowing, and their adoption of key disciplinary aspects. After validation, this could be developed into a future tool to test movement to a deeper understanding of a particular way of knowing (coordinate systems as a first case).

2.6 Proposed work plan

Set out your intended plan of work for the research, indicating important target dates necessary to meet your proposed deadline.

STEPS	DATES
1. Phase 1 – Exploratory phase: IOLab activities at [redacted] (School in Sweden)	April to June 2016 – first activities completed in Sweden (approved by/at Uppsala University).
2. Phase 1 – Exploratory phase: IOLab activities at [redacted] Physics (ECP students)	2nd to 4th quarters 2017. Start of exploratory data collection at [redacted] planned. Shifted due to ethical clearance delays related to disruptions end-2016.
3. Phase 2 – Comparative: IOLab activities at [redacted] Physics (ECP students)	3rd quarter 2017 to 1st 2018– continuation of exploratory phase into comparative study at [redacted].

Please note that the proposed work plan currently only includes the initial phases of the study. Further details and plans will be finalised after the full research proposal and study plan has been approved in March 2017. At that stage we may have to apply for an extension to our ethical clearance.

SECTION 3: ETHICAL ISSUES

The [redacted] Research Ethics Policy applies to all members of staff, graduate and undergraduate students who are involved in research on or off the campuses of [redacted]. In addition, any person not affiliated with [redacted] who wishes to conduct research with [redacted] students and / or staff is bound by the same ethics framework. Each member of the University community is responsible for implementing this Policy in relation to scholarly work with which she or he is associated and to avoid any activity which might be considered to be in violation of this Policy.

All students and members of staff must familiarise themselves with, AND sign an undertaking to comply with, the University's "Code of Conduct for Research".

QUESTION 3.1

Does your study cover research involving:	**YES**	**NO**
Children		×
Persons who are intellectually or mentally impaired		×
Persons who have experienced traumatic or stressful life circumstances		×
Persons who are HIV positive		×
Persons highly dependent on medical care		×
Persons in dependent or unequal relationships		×
Persons in captivity		×
Persons living in particularly vulnerable life circumstances		×

If "Yes", indicate what measures you will take to protect the autonomy of respondents and (where indicated) to prevent social stigmatisation and/or secondary victimisation of respondents. If you are unsure about any of these concepts, please consult your supervisor/ project leader.

QUESTION 3.2

Will data collection involve any of the following:	**YES**	**NO**
Access to confidential information without prior consent of participants		×
Participants being required to commit an act which might diminish self-respect or cause them to experience shame, embarrassment, or regret		×
Participants being exposed to questions which may be experienced as stressful or upsetting, or to procedures which may have unpleasant or harmful side effects		×
The use of stimuli, tasks or procedures which may be experienced as stressful, noxious, or unpleasant		×
Any form of deception		×

If "Yes", explain and justify. If appropriate, indicate what steps will be taken to minimise any potential stress/harm.

QUESTION 3.3

Will any of the following instruments be used for purposes of data collection:	YES	NO
Questionnaire		×
Survey schedule		×
Interview schedule – *see comment below*		×
Psychometric test		×
Other/ equivalent assessment instrument		×

If "Yes", attach copy of research instrument. If data collection involves the use of a psychometric test or equivalent assessment instrument, you are required to provide evidence here that the measure is likely to provide a valid, reliable, and unbiased estimate of the construct being measured. If data collection involves interviews and/or focus groups, please provide a list of the topics to be covered/ kinds of questions to be asked.

Comment: The *potential* interviews will be semi-structured – a set of open-ended and closed questions either based on the task or aspects that may have informed certain actions during engagement with task. Students will be interviewed individually and in a focus group setting to discuss the progression of the task in a stimulated recall setting (shown video data, transcripts). The task- or worksheets (attached) for the activities will be used as the basis for the interview questions.

QUESTION 3.4

Will the autonomy of participants be protected through the use of an informed consent form, which specifies (in language that respondents will understand):	YES	NO
The nature and purpose/s of the research	×	
The identity and institutional association of the researcher and supervisor/project leader and their contact details	×	
The fact that participation is voluntary	×	
That responses will be treated in a confidential manner	×	
Any limits on confidentiality which may apply	×	
That anonymity will be ensured where appropriate (e.g. coded/ disguised names of participants/ respondents/ institutions)	×	
The fact that participants are free to withdraw from the research at any time without any negative or undesirable consequences to themselves	×	
The nature and limits of any benefits participants may receive as a result of their participation in the research	×	
Is a copy of the informed consent form attached?	×	

If NO to any of the above: (a) please justify/explain, and (b) indicate what measures will be adopted to ensure that the respondents fully understand the nature of the research and the consent that they are giving.

QUESTION 3.5

Specify what efforts have been made or will be made to obtain informed permission for the research from appropriate authorities and gate-keepers (including caretakers or legal guardians in the case of minor children)?

In Uppsala at the high school, we have obtained ethical clearance from all the relevant authorities. This document makes application for the part of the study involving [redacted] students. There have been discussions between the investigator (myself) and the Head of Department of Physics, and with the PC lab manager in the Physics building and colleagues (fellow lecturer [redacted] who has taken over course coordination, the two teaching assistants and the demonstrators in ECP PHY[redacted]). The HOD, Prof. [redacted] gave his consent, and the PC lab manager and colleagues indicated their willingness to facilitate the performing of the tasks (IOLab involves using interface software for real-time readout on a computer screen graph), assisting with facilitation (facilitator-student engagement about the task) and video recording specifically identified students (who will agree beforehand by signing consent forms) and the classroom in general. Students not wishing to be recorded in the general class settings (physics laboratory and lecture periods) will be placed in a part of the room that is not visible on the video footage. For sessions involving only research groups the same measures apply.

QUESTION 3.6

STORAGE AND DISPOSAL OF RESEARCH DATA:
Please note that the research data should be kept for a minimum period of at least five years in a secure location by arrangement with your supervisor.

How will the research data be secured and stored? When and how (if at all) will data be disposed of?

At the Division for Physics Education Research, all signed consent forms, personal data including video and audio recordings, transcripts and all other personally identifiable information will be scanned (if relevant) and uploaded onto a secure data server in the office of the program responsible professor (professor responsible for the research program in which the project is located). Hard copies will also be kept in a locked office in a lockable cabinet for a minimum of five years. Thereafter a decision will be made whether to keep the records or to dispose of paper copies (by shredded) and / or electronic data (by permanent deletion from data servers, drives and personal computers).

QUESTION 3.7

In the subsequent dissemination of your research findings – in the form of the finished thesis, oral presentations, publication etc. – how will anonymity/ confidentiality be protected? Original names of participants will be substituted with fictionalized names (alphanumeric swapping scheme). Still images or video clips will be edited so that no facially recognizable images or clips are used if a student requests this, e.g. oval shape to blot out faces, outline sketches, etc. audio muted and replaced with subtitled text (for presentation purposes). In the event of a need to use full video clips including faces and audio (gestures, comment intonations and facial expressions may be key to the analysis), students will be contacted and requested to sign a revised consent form giving explicit consent to use such data.

QUESTION 3.8

Is this research supported by funding that is likely to inform or impact in any way on the design, outcome and dissemination of the research?	**YES**	**NO**
		×

If yes, this needs to be explained and justified.

QUESTION 3.9

Has any organization/company participating in the research or funding the project, imposed any conditions to the research?	**YES**	**NO**
		×

If yes, please indicate what the conditions are.

QUESTION 3.10

Do you, or any individual associated with or responsible for the design of the research, have any personal, economic, or financial interests (or any other potential conflict of interests) that could reasonably be regarded as relevant to this research project?	**YES**	**NO**
		×

If you answered YES to Question 3.10 please provide full details:

SECTION 4: FORMALISATION OF THE APPLICATION

APPLICANT

I have familiarised myself with the University's Code of Conduct for Research and undertake to comply with it. The information supplied above is correct to the best of my knowledge.
NB: PLEASE ENSURE THAT THE ATTACHED CHECK SHEET IS COMPLETED
DATE: 2016/10/31 **SIGNATURE OF APPLICANT: ________________________**

SUPERVISOR/PROJECT LEADER/DISCIPLINE ACADEMIC LEADER

NB: PLEASE ENSURE THAT THE APPLICANT HAS COMPLETED THE ATTACHED CHECK SHEET AND THAT THE FORM IS FORWARDED TO YOUR SCHOOL RESEARCH COMMITTEE FOR FURTHER ATTENTION
DATE: 2016/10/31 **SIGNATURE OF SUPERVISOR/ PROJECT LEADER/DISCIPLINE LEADER** ____

RECOMMENDATION OF FACULTY RESEARCH ETHICS COMMITTEE/HIGHER DEGREES COMMITTEE

The application is (please tick):

	Recommended and referred to the Human and Social Sciences Research Ethics Committee for further consideration
	Not Approved, referred back for revision and resubmission
	Other: please specify:

NAME OF CHAIRPERSON:

________________________________SIGNATURE:__________________________

DATE ....

RECOMMENDATION OF UNIVERSITY RESEARCH ETHICS COMMITTEE (HUMAN AND SOCIAL SCIENCES)

NAME OF CHAIRPERSON:______________________________SIGNATURE______________________

DATE..

CHECK SHEET FOR APPLICATION

PLEASE TICK

1. Form has been fully completed and all questions have been answered	✓
2. Questionnaire attached (where applicable)	✓
3. Informed consent document attached (where applicable)	✓
4. Approval from relevant authorities obtained (and attached) where research involves the utilisation of space, data and/or facilities at other institutions/organisations	✓
5. Signature of Supervisor / project leader	✓
6. Application forwarded to Faculty Research Committee for recommendation and transmission to the Research Office	✓

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