

Perspectives on the role of digital tools in students' open-ended physics inquiry

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Licentiate dissertation presented at Uppsala University to be publicly examined in Room 4001, Ångströmlaboratoriet, Lägerhyddsvägen 1, Uppsala, Wednesday, 29 May 2019 at 08:15. The examination will be conducted in English. Opponent: Dr. Konrad Schönborn (Department of Science and Technology, Linköping University).

Abstract

Euler, E. 2019. Perspectives on the role of digital tools in students' open-ended physics inquiry. 170 pp. Uppsala.

In this licentiate thesis, I present detailed case studies of students as they make use of simulated digital learning environments to engage with physics phenomena. In doing so, I reveal the moment-to-moment minutiae of physics students' open-ended inquiry in the presence of two digital tools, namely the sandbox software *Algodo* and the PhET simulation *My Solar System* (both running on an interactive whiteboard). As this is a topic which has yet to receive significant attention in the physics education research community, I employ an interpretivist, case-oriented methodology to illustrate, build, and refine several theoretical perspectives. Notably, I combine the notion of semi-formalisms with the notion of Newtonian modeling. I illustrate how *Algodo* can be seen to function as a Papertian microworld, I meaningfully combine the theoretical perspectives of social semiotics and embodied cognition into a single analytic lens, and I reveal the need for a more nuanced taxonomy of students' embodiment during physics learning activities. Each of the case studies presented in this thesis makes use of conversation analysis in a fine-grained examination of video-recorded, small-group student interactions. Of particular importance to this process is my attention to students' non-verbal communication via gestures, gaze, body position, haptic-touch, and interactions with the environment. In this way, I bring into focus the multimodally-rich, often informal interactions of students as they deal with physics content. I make visible the ways in which the students (1) make the conceptual connection between the physical world and the formal/mathematical domain of disciplinary physics, (2) make informal and creative use of mathematical representations, and (3) incorporate their bodies to mechanistically reason about physical phenomena. Across each of the cases presented in this thesis, I show how, while using open-ended software on an interactive whiteboard, students can communicate and reason about physics phenomena in unexpectedly fruitful ways.

Keywords: digital learning environments, modeling, semi-formalisms, microworlds, social semiotics, embodied cognition, disciplinary-relevant aspects.

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To my parents

Peer-reviewed academic work

This licentiate thesis is based around the work included in the following papers, which I will refer to throughout the text by Roman numeral (i.e. Paper I, Paper II, etc.). For all of the papers, I was responsible for the crafting of the original idea, the implementation of the analysis, and the writing of the manuscript. Reprints are made with permission from the respective publishers.

- Euler, E. & Gregorcic, B. (2018) Exploring how students use a sandbox software to move between the physical and the formal. In *2017 Physics Education Research Conference Proceedings* (pp. 128–131). American Association of Physics Teachers.
- Euler, E. & Gregorcic, B. (Accepted) Algodoo as a Microworld: Informally Linking Mathematics and Physics. In *Mathematics in Physics Education*, edited by G. Pospiech, M. Michelini, & B. Eylon (Springer).
- Euler, E., Rådahl, E., & Gregorcic, B. (Accepted) A social-semiotic look at embodiment in physics learning. *Physical Review Special Topics – Physics Education Research*.

Other supporting work

This licentiate also draws from the following work.

Conference Presentations

- Euler, E. & Gregorcic, B. (2016) *Fostering Multimodal Communication in Physics Learning Through the Inclusion of Digital Sandbox Software Modeling Alongside Laboratory Experiments*. Paper presented at the 8th International Conference on Multimodality (8ICOM), Cape Town, South Africa, December.
- Euler, E. & Gregorcic, B. (2017) *Physics Students' Use of Algodoo in Modeling*. Paper presented at the American Association of Physics Teachers (AAPT) Summer Meeting, Cincinnati, OH, July 24-26.
- Euler, E. & Gregorcic, B. (2018) *Playful, scientific inquiry in an open-ended physics software*. Paper presented at the Från forskning till fysikundervisning Conference, Lund, Sweden, April 10-11.
- Euler, E., Rådahl, E., & Gregorcic, B. (2018) *Interpersonal Touch as a Meaning-Making Resource in the Teaching and Learning of Physics*. Paper presented at the Uppsala Research School in Subject Education (UpRISE) Conference, Uppsala, Sweden, May 16.
- Euler, E., Rådahl, E., & Gregorcic, B. (2018) *Metaphorical Use of Touch in an Astronomy Activity*. Paper presented at the Konferens för lärarstudenter, Uppsala Research School in Subject Education (UpRISE), Uppsala, Sweden, June 14.
- Euler, E., Rådahl, E., & Gregorcic, B. (2018) *A student-generated embodied metaphor for binary star interactions*. Paper presented at the American Association of Physics Teachers (AAPT) Summer Meeting, Washington, D.C., July 28-August 1.
- Euler, E., Rådahl, E., & Gregorcic, B. (2018) *Spontaneous use of dance in an astronomy activity*. Paper presented at the 9th International Conference on Multimodality (9ICOM), Odense, Denmark, August 15-17.
- Euler, E., Gregorcic, B., & Linder, C. (2018) *Discovering variation: learning physics in a creative digital environment*. Paper presented at the European Association for Research on Learning and Instruction (EARLI) Special Interest Group 9 (SIG9) Conference, Birmingham, UK, September 16-18.

Conference Posters

- Euler, E. & Gregorcic, B. (2017) *Semi-formal Modeling in Algodoo*. Poster presented at the American Association of Physics Teachers (AAPT) Summer Meeting, Cincinnati, OH, July 24-26.
- Euler, E. & Gregorcic, B. (2017) *Exploring How Students use a Sandbox Software to Move between the Physical and the Formal*. Poster presented at the Physics Education Research Conference (PERC), Cincinnati, OH, July 26-27.
- Euler, E. & Gregorcic, B. (2018) *Exploring how students use sandbox software to move between the physical and the formal*. Poster presented at the Teknisk-naturvetenskapliga fakultetens universitetspedagogiska konferens (TUK Conference), Uppsala, Sweden, March 13.
- Euler, E., Rådahl, E., & Gregorcic, B. (2018) *Embodying the abstract or abstracting from the body*. Poster presented at the American Association of Physics Teachers (AAPT) Summer Meeting, Washington, D.C., July 28-August 1.
- Euler, E. & Gregorcic, B. (2018) *The case for (better) illustrations in qualitative physics education research*. Poster presented at the Physics Education Research Conference (PERC), Washington, D.C., August 1-2.
- Euler, E. (2019) *The history of digital technology in Physics Education Research*. Poster presented at the Teknisk-naturvetenskapliga fakultetens universitetspedagogiska konferens (TUK Conference), Uppsala, Sweden, March 19.

Contents

Notes for the reader	xv
1 Introduction	1
1.1 Who should read this licentiate thesis?	2
1.2 Research questions	3
1.3 The knowledge claims of this thesis	4
1.4 Structure of the thesis	4
2 Literature review	5
2.1 Physics education research	5
2.1.1 The historical development of PER	6
2.1.2 The topical areas of PER	11
2.1.3 My position in the Docktor-Mestre map of PER	18
2.2 Instructional technology in PER	19
2.2.1 The paradigmatic development of PER-IT	19
2.2.2 The topical areas of PER-IT	29
2.2.3 My position in PER-IT	35
2.3 Language and social interaction in PER	36
2.3.1 The ‘embodied turn’ in LSI research	36
2.3.2 The existing PER-LSI work and my position in it	40
2.4 The perspectives taken in this thesis	41
2.4.1 Constructionism and microworlds ^{II}	42
2.4.2 Semi-formalisms and modeling ^I	43
2.4.3 Multimodal social semiotics ^{III}	44
2.4.4 Multimodal conversation analysis ^{III}	45
2.4.5 Embodied cognition and conceptual metaphor ^{III}	46
2.4.6 Kinesthetic/embodied learning activities ^{III}	48
2.5 Summary of literature review	50
3 The digital tools studied	51
3.1 <i>Algodo</i> ^{II}	51
3.2 <i>My Solar System</i> ^{III}	54
3.3 The interactive whiteboard ^{II}	54
4 Methodology	56
4.1 Case-oriented research	56
4.2 Data collection	58

4.2.1 The first data set ^{I & II}	59
4.2.2 The second data set ^{II}	61
4.2.3 The third data set ^{III}	63
4.3 General analytic approach	64
4.3.1 Presentation of data: multimodal transcription	64
4.4 Establishing trustworthiness and ethical integrity	69
4.4.1 Trustworthiness	69
4.4.2 Ethical considerations	75
5 Analysis and discussion of cases	79
5.1 Paper I	79
5.1.1 Selection of data	80
5.1.2 Transcription ^I	80
5.1.3 Analysis and discussion ^I	81
5.2 Paper II	85
5.2.1 Informal Physics Learning ^{II}	85
5.2.2 Selection of data ^{II}	87
5.2.3 Transcription ^{II}	87
5.2.4 Case 1: Vector-sense with the ‘Velocity’ tab ^{II}	88
5.2.5 Case 2: Kinematics with ‘Show Plot’ ^{II}	96
5.3 Paper III ^{III}	104
5.3.1 Selection of data ^{III}	105
5.3.2 Transcription ^{III}	106
5.3.3 Orbital motion ^{III}	107
5.3.4 The orbital periods of binary stars ^{III}	107
5.3.4 Analytic model ^{III}	110
5.3.4 Analysis and discussion ^{III}	112
5.3.5 Synthesis and discussion ^{III}	129
6 Synthesis of findings	133
6.1 Research Question 1a ^I	133
6.2 Research Question 1b ^{II}	134
6.3 Research Question 1c ^{II}	135
6.4 Research Question 2 ^{III}	135
6.5 Research Question 3 ^{III}	136
6.6 Synthesizing across the three papers	138
7 Contributions and implications	140
7.1 Theoretical contributions	140
7.2 Methodological contributions	141
7.3 Implications for the teaching and learning of physics	141
8 Future work ^I	143
Acknowledgements	144

References.....	146
Appendix A: Consent forms used for the first data set.....	171
Appendix B: Consent form used for the second data set	177
Appendix C: Consent forms used for the third data set.....	181
Appendix D: Transcript from the first data set.....	185
Appendix E: Transcript from the third data set.....	203

Abbreviations

AI	<i>Artificial Intelligence</i>
BBN	<i>Bolt, Beranek, and Newman</i>
CAI	<i>Computer-Assisted Instruction</i>
CC	<i>Computer Constructivism</i>
CSCL	<i>Computer-Supported Collaborative Learning</i>
CUPLE	<i>Comprehensive Unified Physics Learning Environment</i>
DBER	<i>Discipline-Based Education Research</i>
DRA	<i>Disciplinary Relevant Aspect</i>
ELA	<i>Embodied Learning Activity</i>
EU	<i>European Union</i>
FCI	<i>Force Concept Inventory</i>
FMCE	<i>Force and Motion Concept Evaluation</i>
HCIs	<i>Human Computer Interfaces</i>
IT	<i>Instructional Technology</i>
KLA	<i>Kinesthetic Learning Activity</i>
LSI	<i>Language and Social Interaction</i>
MUPPET	<i>Maryland Project in Physics and Education Technology</i>
NRC	<i>National (American) Research Council</i>
PER	<i>Physics Education Research</i>
PhET	<i>Physics Education Technology</i>
PLATO	<i>Programmed Logic for Automatic Teaching Operations</i>
SFT	<i>Systemic Functional Theory</i>

Notes for the reader

The use of language

Throughout this licentiate thesis, I use the singular pronoun ‘I’ rather than the collective pronoun ‘we.’ This is a stylistic choice I made in order to improve the flow between sections and to reduce ambiguity between instances when the ‘we’s’ may have been referring to different collections of collaborators. Nonetheless, the three papers on which this licentiate thesis is based were each crafted through my collaborative efforts with various coauthors (see ‘use of previous work,’ below).

Furthermore, in order to avoid the clumsy ‘he/she’ and ‘his/hers’ pronouns when referring to a nondescript individual in the third person, this licentiate thesis occasionally makes use of the singular ‘they’ and ‘their’ pronouns.

The use of previous work

On occasion throughout various sections of this thesis, I make use of (i.e. ‘recycle’) portions of text which originally appear in Papers I, II, and III. At each of these instances where I engage in such recycling, I denote the original source with a roman numeral superscript (e.g. a section which has been recycled in part from Paper II would be labelled as Section ^{II}). My reason for textual recycling – which to some academic minds might appear as an example of unscrupulous ‘self-plagiarism’ – is to quite literally *build* a comprehensive story from all three of my papers. In this licentiate thesis, I have strung together a patchwork of original material and previously-crafted material in an effort to synthesize a new, single narrative thread representing my doctoral work thus far. Nonetheless, I understand that by recycling previously coauthored work as part of this otherwise solely-authored thesis, I run the risk of implying that my coauthors’ work is entirely my own. This is not my intention. Each paper was crafted out of a collaborative effort and I have attempted to acknowledge my colleagues’ efforts (and flag the instances of recycling, for transparency’s sake) by referencing the appropriate paper from which I have recycled at every turn. The topic of plagiarism and textual recycling is certainly one worth addressing (see, for example, Bruton (2014) for a thorough discussion). Therefore, I opt for complete transparency here and throughout the remainder of the licentiate thesis.

1 Introduction

In 1989, Jack M. Wilson and Edward F. Redish published an article on the use of computers for teaching physics wherein they mentioned a piece by the *Wall Street Journal*, which had run earlier that year under the headline of “Computers Failing as Teaching Aids.” The main reasons given by the *Wall Street Journal* for the failure of educational technology in 1989 were a “lack of access to computers, poor software, and faculty members who are inadequately prepared to use computers effectively” (J. M. Wilson & Redish, 1989, p. 34). Thirty years later, at the time of writing this licentiate thesis, the very nature of computers and digital technology available to physics teachers has changed tremendously. Most people now have powerful digital tools in their pockets that far exceed the computers of the 1980s and myriad new technologies (both hardware and software) continue to emerge at a breakneck pace to far-reaching consequence. In relation to the first of the *Wall Street Journal*’s grievances with computers – the point about lack of access – much of the world has certainly surpassed their prerequisite of availability.

In fact, with an overwhelming abundance of digital technology now available, a general question about technology’s utility in teaching must now be answered with a resounding, ‘*it depends.*’ Even within the context of physics education, the amount and diversity of technology used in physics education are too large for anyone to be able to make broad and overarching generalizations about the impact of digital technology on physics teaching and learning. In particular contexts, however, specific digital tools have been reported to have positive effects on learning. For example, highly specialized educational simulations and microcomputer-based laboratory tools have each been shown to help students develop conceptual understanding in physics (e.g. Finkelstein, Adams, et al., 2005; Thornton & Sokoloff, 1990a). Still, insights into *how* such technologies are used by students during the process of learning physics are relatively scarce in the research literature. This is especially true for physics learning activities, where students work collaboratively, such as using digital tools in group-work.

In response to the *Wall Street Journal*’s last point – that faculty members are not adequately prepared to use technology effectively – the physics education research community must continually provide insights into the ways digital technologies can be used to benefit physics teaching and learning. A key question today, the answer to which will inevitably evolve with technology itself, is thus: how do students engage with digital tools when learning

physics, and what are the ways in which students' engagement with digital tools can open-up the possibilities for learning physics? As I have argued, a general answer to this multipart question is not necessarily obtainable. Instead, one must pose this question in relation to particular contexts and specific technologies.

My licentiate thesis represents my foray into addressing this question through the study of a particular kind of digital tool used in a specific context. I explore the ways in which simulated digital environments can be leveraged by small groups of students while they engage with physics content. In particular, I have focused on how students make use of simulated digital environments such as the open-ended, sandbox-like software, *Algodo*, and the *My Solar System* simulation software (PhET, 2018). My exploration of these digital tools is one where I emphasize students' moment-to-moment interaction with one another and with the technology. Thus, I am able to explore *how* digital tools are used in a fine-grained sense. The approach used in this licentiate thesis involves multiple theoretical perspectives, among them *multimodal social semiotics* – which concerns itself with how meaning is made by people within social contexts through a range of meaning-bearing systems (i.e. talk, gesture, diagrams, etc.) – and *embodied cognition* – which concerns itself with how the embodied (largely common) experiences of individuals shape the ways in which they reason and communicate. I show that insights into students' use of digital tools can be made not only by studying students' engagement with the tools themselves, but also by paying attention to the rich interpersonal interactions between students that these tools seem to enable and foster.

1.1 Who should read this licentiate thesis?

This licentiate thesis is first and foremost a project of physics education research (PER). Thus, it follows that the intended audience is the community of researchers interested in the teaching and learning of physics. Yet, there exists a wide spectrum to the work done within PER: some researchers being more concerned with changing teaching practices by developing curricular materials and others more focused on informing future research by developing theoretical frameworks and methodologies. In this thesis, I have focused on expanding a collection of theories which I have found pertinent to students' interaction around digital tools, and as such, I see myself more closely aligned with the latter approach.¹ Thus, considering the wide spectrum of PER, the

¹ This is not to say that this licentiate thesis will not be of any interest to curricular designers. In fact, I make occasional recommendations about the way that physics might be taught throughout this thesis. Additionally, I hope that physics teachers can find value in the theoretical discussions contained in this thesis, provided they allow themselves to personally relate to any of the cases studied herein.

findings in this thesis will be of *particular* interest to those physics education researchers interested in the development of theory.

However, as I will discuss in Chapter 2, this licentiate thesis also relates to research on instructional technology and on language and social interaction. This thesis will therefore also be of interest to designers and implementers of digital, educational tools, especially those concerned with how technologies are used by groups of students on a moment-to-moment basis. Likewise, linguists, anthropologists, and semioticians who are interested in physics students' communication and interactions around technology may also find this thesis of interest.

1.2 Research questions

As stated in the preceding section, the aim of this licentiate thesis is to explore the ways in which open-ended, sandbox-like digital tools are used by small groups of physics students to make meaning. In order to do so, I have developed the following research questions.

- RQ 1. During open-ended inquiry, how can sandbox-like, construction-based digital learning environments like Algodoo*
- (a) act as a mediator for students between the physical world and the formal, mathematical representations of physics?*
 - (b) provide students with alternative access to physics-relevant mathematical representations?*
 - (c) motivate students to use physics-relevant mathematical representations?*
- RQ 2. How can the theoretical perspective of social semiotics be meaningfully combined with cognitive perspectives on embodiment for research on physics teaching and learning?*
- RQ 3. Using the combined perspective from Research Question 2, how do students working in a digitally-rich environment make use of embodied, non-disciplinary meaning-making resources to reason about binary star dynamics in ways that relate to aspects deemed relevant by the physics discipline?*

Each of these research questions, with the exception of Question 2, have been answered using a fine-grained analysis of cases of students' small group interactions around digital tools. Question 2 is a theoretical/methodological question which is answered in service of Question 3.

1.3 The knowledge claims of this thesis

The work in this thesis is based on the fine-grained study of four cases where small groups of students made use of the digital tools for the purposes of physics learning. It makes contributions across three main research fronts:

- Physics education research: This licentiate thesis provides an in-situ examination of students' use of digital tools in a manner which has rarely been conducted before and to a degree which further develops existing theoretical frameworks for the future investigation of physics teaching and learning.
- Research on instructional technology: This licentiate thesis provides an examination of socially-embedded instructional technology use which showcases how physics students can use digital tools in combination with physical apparatuses, mathematical representations, and their own bodies.
- Research on language and social interaction: This licentiate thesis meaningfully synthesizes the existing frameworks of embodied cognition and social semiotics within the context of digitally-rich physics learning environments.

1.4 Structure of the thesis

My licentiate thesis is structured as follows. In Chapter 2, I present an overview of physics education research, research on instructional technology, and research on language and social interaction. In doing so, I review the relevant literature and position the research of this thesis. In Chapter 3, I explain the digital tools which I have studied in this thesis – namely, *Algodo*, the PhET simulation *My Solar System*, and the interactive whiteboard. In Chapter 4, I discuss the interpretivist, case-oriented methodology used across the three papers that constitute this thesis. Then, in Chapter 5, I present the analyses and findings from each of the three papers. I synthesize these results in Chapter 6, along with showing how my work has answered each of my research questions. In chapter 7, I summarize the theoretical and methodological contributions of this thesis and list some of the implications for the teaching and learning of physics. Finally, in Chapters 8, I discuss the future work which will lead to my doctoral thesis. In the appendices, I have included the consent forms used, the transcript generated for the first data set, and a detailed transcript generated for the analysis of Paper III (including the original Swedish used by the students from that data set). As is customary with Swedish theses, all three of the papers which make up this licentiate thesis are included in full at the end.

2 Literature review

This chapter provides an overview of the literature which pertains to the various perspectives taken in this licentiate thesis. As discussed in the introduction, my research has been first and foremost a project within physics education research (PER), but has simultaneously related to and drawn from two other research fields which I refer to as instructional technology (IT) and language and social interaction (LSI). It is, therefore, worthwhile to reflect on how this thesis can be defined in relation to the existing literature of each of these three fields. In doing so, I will make a case for the novelty and relevance of my research, not only insofar as I have examined underexplored topics in the fields of PER, IT, and LSI, respectively, but also due to the extent to which I have uniquely synthesized various perspectives in the pursuit of answering my research questions.

The structure of this chapter is as follows. I will devote a section to each of the three relevant research fields – PER in Section 2.1, IT in Section 2.2, and LSI in Section 2.3 – wherein I will review how each field has historically developed and survey the diversity of topical areas of which each field is constituted. In my discussion of the IT and LSI research fields, I will pay specific attention to the subset of topics which are germane to PER. That is to say, Section 2.2 will highlight the IT-related work within PER and Section 2.3 will highlight the LSI-related work within PER. As I review each section, I will also reflect on how the work done in this thesis is situated in relation to these fields. In a final section (2.4), I will summarize the unique theoretical perspectives this thesis takes at the intersection of PER, IT, and LSI, especially in terms of constructionism, semi-formal modeling, multimodality, social semiotics, embodied cognition, and conceptual metaphor.

2.1 Physics education research

Physics education research (PER) is an academic field generally concerned with investigating how people teach and learn physics, though the breadth of research projects within (or at least associated with) PER defies any singular description. Historically, researchers of the PER community have tended to be housed *within* physics departments, where they purport to apply physics-specific expertise to the study of physics education at the university level. In this capacity, PER can be considered a specific instantiation of discipline-

based education research (DBER). By DBER I mean those enterprises which “[investigate] learning and teaching in a discipline from a perspective that reflects the discipline’s priorities, worldview, knowledge, and practices,” but which is complementary to and informed by research on learning and cognition done elsewhere (National Research Council, 2012, p. 1).²

It is important to note that overwhelming majority of PER has occurred (and continues to occur) in universities within the U.S. Due to the relative scarcity of non-American³ PER work – and, perhaps, because of the sufficient size of the American PER community by itself – most reviews of the field have been made by American authors who fail to mention many PER efforts outside the U.S. This tends to portray PER community as an exclusively American one. However, there is (and for most of PER’s history, has been) non-American PER work which is worth recognizing. Similarly, while a large portion of PER is done in physics departments at the university level, a growing amount of research on physics education is being done in departments of education (Beichner, 2009), often with a focus on pre-university physics. Such projects are typically referred to under the umbrella of ‘science education research’ rather than PER, however, and many science education researchers are less concerned with a discipline-based approach than is the average physics education researcher. In the section that follows, I review the field of PER, first in terms of its historical development and then as an overview of its topical areas. As I do so, I will attempt to include all of the relevant⁴ non-American work and science education work of which I have been made aware.

2.1.1 The historical development of PER

To begin, I review the development of PER as a field of study. I structure my review around four eras: (1) before 1970, (2) from 1970 to 1989, (3) from 1990 to 1998, and (4) since 1998 (adapted from Cummings, 2011).

Pre-1970: The Prelude Events

The field of U.S. PER began to take form in the 1970s, borne from a crucible of emerging theories of learning, a Sputnik-era swell in science funding, and early projects to develop science curricula. On the topic of learning theories, American education theorist/philosopher John Dewey (1938) and Swiss

² While I have found this to be a useful definition for DBER from the American National Research Council (NRC), in using it I do not intend to suggest, by association, that I condone all of the recommendations for DBER that the NRC produced in this report.

³ Here and throughout this chapter, I use American as the demonym for residents or natives of the United States.

⁴ Admittedly, what I have found to be relevant is a matter of perspective, but I hope in highlighting some oft-overlooked sources that I can avoid the pattern of exclusion which has left so much important work unnoticed. I would also add that this is an ongoing project of mine (and my research colleagues), so I hope that quite a bit more of the relevant, non-American PER will be added to this review in my doctoral thesis.

psychologist Jean Piaget (1928) had both contributed significantly to a ‘constructivist’ theory of knowing in the first half of the century. This theory considered learning as an individual’s bringing-together of prior knowledge with newly-encountered information in a process of mental construction. Meanwhile, American psychologist B. F. Skinner (1938) had popularized a ‘descriptive behaviorism’ perspective to learning, in which the internal learning process is regarded as a black box with inputs (conditioning) and outputs (learning outcomes) (De Jong, 2007). Both of these psychological theories of learning would come to shape not only the early PER work in the U.S. but also the “first wave” of science education reform across the western world in the 1960s (De Jong, 2007, p. 16).

In 1957, the Soviet Union’s landmark launch of the Sputnik satellite exposed what the American public and policymakers saw as the relative inferiority of American science and technology capabilities. A public desire for future physicists had already spiked after the Second World War, resulting in the creation of the National Science Foundation (NSF) in 1950 and influential education reform projects such as the Physical Science Study Committee (PSSC) in 1956 (Cummings, 2011; Meltzer & Thornton, 2012). However, the frenzy provoked by Sputnik, alone, triggered an order of magnitude increase in federal funding for American mathematics and science education programs (Krieghbaum & Rawson, 1969; Meltzer & Otero, 2015). Aside from producing a “critical mass of fairly young, well trained physicists available and willing to investigate [what] PER had to offer” (Cummings, 2011, p. 5), the increased funding for curriculum projects during this period worked to elevate the prestige and value of education work among career physicists (Reif, 2010 in Cummings, 2011, p. 4).

In 1948, Europe saw the creation of the Organisation for European Economic Cooperation (OEEC) to aid in the reconstruction of the war-battered, post-WWII continent (European University Institute, 2019). By the 1960s – likely spurred on by the success of Sputnik as the Americans were – the OEEC had arranged a series of international gatherings to reform physics teaching. When the OEEC discontinued its support for these gatherings, a group of previous attendees founded the International Research Group on Physics Teaching (GIREP)⁵ as a working group to improve pre-university physics (Koupil, 2008).

During this surge of monetary support for science education, several key curriculum development projects began which would form the foundation of modern PER, particularly in the U.S. (Meltzer & Otero, 2015). In 1959, Robert Karplus, a Berkeley physicist who had previously worked in theoretical quantum mechanics, began incorporating laboratory-based learning cycles into K-6 science education as part of the Science Curriculum Improvement Study (SCIS) (Cummings, 2011). Frederick Rief, a physicist with previous

⁵ In the original French, Groupe International de Recherche sur l’Enseignement de la Physique.

experience in superfluids, co-founded the Graduate Group in Science and Mathematics Education (SESAME) at Berkeley with Karplus in 1969 (Cummings, 2011; Fuller, 2002). Arnold Arons, also a theoretical physicist by trade, worked on curriculum development for college physics in the early 1960s and moved to the University of Washington in 1968 to work with pre-service physics teachers (Arons, 1998; Cummings, 2011). Each of these physicists-turned-science-curriculum-developers laid much of the groundwork for early PER researchers.

Thus, following the emergence of new psychological theories of learning, a reactionary Sputnik-era investment from policymakers to reform science education, and consequently, the establishing of several pivotal curriculum development projects, the 1970s had sufficient means for the emergence of modern PER. Cummings (2011) refers to this period from around 1930 to 1970 in the U.S. as the “Prelude Events” (p. 10) (see Figure 1).

1970-1989: The Early Years

In the next two decades, which Cummings (2011) labels as the “Early Years” (p. 12), modern PER at the university level truly began. From the 1970s through the 1980s, interested academics began to develop investigative research techniques, started amassing a knowledge base of student difficulties with physics, and established PER as a community with self-governing and advocacy efforts. Lillian McDermott was an early pioneer in developing physics curricula for underrepresented populations (e.g. McDermott, Piternick, & Rosenquist, 1980a, 1980b, 1980c) and for the preparation of pre-college teachers (e.g. McDermott, 1974), which she motivated with research on physics students’ reasoning (Rosenquist & McDermott, 1987). McDermott’s two papers with David Trowbridge – who in 1979 had earned the first ever physics

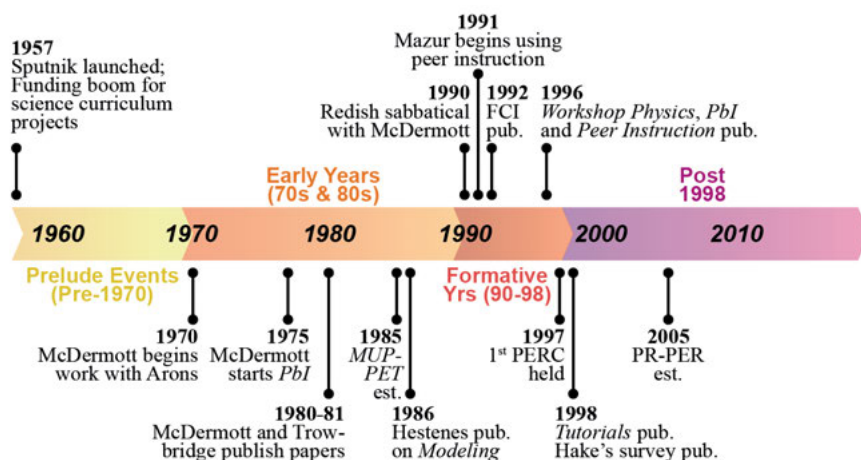


Figure 1. A timeline of some of the major events in the development of PER, adapted from Cummings (2011).

PhD for PER work (Cummings, 2011) – on the topic of one-dimensional motion are considered to be among the most important of this era (Trowbridge & McDermott, 1980, 1981). It was also around this time that McDermott began working on the (now influential) *Physics by Inquiry* curriculum (Cummings, 2011). Other important work from this time includes Rief et al.’s (1976) work on problem-solving skills at Berkeley and Viennot’s (1979) work on ‘spontaneous reasoning’ in France. With the advent of microprocessors, other were inspired to generate programming-focused curricula (e.g. MacDonald, Redish, & Wilson, 1988) and microcomputer-based sensors for the physics laboratory (e.g. Laws, 1991; Thornton & Sokoloff, 1990) (see Section 2.2 for a discussion of these technologies and more).

A key aspect of the “Early Years” of PER was the researchers’ concerted effort to improve on the transmissionist approaches offered by behavioral psychology. Especially by the 1980s, science education researchers across the western world sought to study the “throughput of the ‘black box’” (De Jong, 2007, p. 17) in order to better understand the learning process itself. As part of this effort, early physics education researchers documented students’ own ideas shaped through everyday experiences and brought into the physics classroom.⁶ Thereafter, as the recurrence of certain student difficulties with motion and forces became more evident, researchers were able to develop curricula which accounted for these common difficulties. Likewise, researchers were able to create the first conceptual inventories which probed students’ conceptual understanding of fundamental physics concepts (e.g. Halloun & Hestenes, 1985). It is during this era that the constructivist learning theories of Piaget and his contemporaries firmly entered the work of early physics education researchers in the form of studies on conceptual understanding. By 1989, the collection of few physicists who had started to pursue PER at the university level from the 1970s had increased to the point that as many as ten American universities housed PER faculty members in their departments of physics.

1990-1998: The Formative Years

From 1990 to around 1998, in an era termed the “Formative Years” of PER (Cummings, 2011, p. 15), many influential events occurred for the field. For one, Edward Redish – a physics education researcher from the University of Maryland who had studied how to incorporate computer programming in the physics classroom since the mid-1980s – went on a sabbatical with Lillian McDermott at the University of Washington from 1990 to 1991. Cummings claims that by the time that Redish returned, he had “reinvigorated” some of the field of PER to move beyond its conceptual focus and encouraged researchers to investigate non-subject material content such as epistemology and students’ attitudes and beliefs (2011, p. 15). Whether spurred on by Redish or

⁶ Thereby, eschewing the types of ‘tabula rasa’ (blank slate) instructional models which took uneducated students to be empty vessels into which knowledge needed to be transmitted.

not, many researchers began to take up theoretical discussions during this era that would later shape the landscape of future PER projects (e.g. diSessa, 1993; Hammer, 1994; Linder, 1993).

Another influential event during this era was the publication of the Force Concept Inventory (FCI) (Hestenes, Wells, & Swackhamer, 1992),⁷ which comprised a series of deceptively easy multiple choice conceptual questions. For many physics professors, the FCI seemed almost too basic to administer to students at the university level, yet the consistently poor results often showed how uncommon a conceptual understanding of physics was, even at highly-ranked institutions. In 1998, Hake published a meta-study of six thousand students' FCI scores, showing that conceptual learning gains were significantly better for those courses which used interactive engagement, inquiry-based instructional methods rather than traditional lecture (Hake, 1998). This paper made a clear case for the utility of PER-based instructional strategies (and diagnostic tools) for shaping the physics classroom.

It was also during this period that important “interactive engagement” curricula were published. These instructional approaches were aimed at improving students' conceptual understanding by encouraging their active participation in the classroom learning process. For example, Harvard's Eric Mazur implemented and later published his widely popular *Peer Instruction* approach during this time (Mazur, 1997). Other curricula published in these “Formative Years” of PER including *Modeling Instruction* (Hestenes, 1992; Jackson, Dukerich, & Hestenes, 2005; Wells, Hestenes, & Swackhamer, 1995), *Workshop Physics* (Laws, 1991; Laws, Willis, & Sokoloff, 2015), *Physics by Inquiry* (McDermott, Shaffer, & Rosenquist, 1996b), and the *Tutorials in Introductory Physics* (McDermott, Shaffer, & University of Washington Physics Education Group, 1998).

Post-1998

In the period following 1998, the field of PER has become increasingly accepted by the wider physics community. In 1999, the American Physical Society (APS) recognized PER as a crucial part of the physics discipline, advocating for the acceptance of PER within physics departments to facilitate “close contact between the physics education researchers and the more traditional researchers who are also teachers” (APS Council, 1999, p. 4). In similar fashion, the European Physical Society (EPS) created the Physics Education Division in 2000 (European Physics Society, 2019). Furthermore, in the last two decades, more recent PER projects have begun to incorporate increasingly diverse research methodologies (borrowing from such fields as linguistics, complexity theory, and gender studies, for example). In particular – as has

⁷ Though the FCI is arguably one of the first and most influential of the concept tests in PER, previous work had been done outside the U.S – in South Africa – to test students' difficulties with physical concepts more than a decade earlier (Helm, 1978).

been the international trend in science education research (De Jong, 2007) – PER has begun embracing a diversity of learning theories (e.g. Brewe, Kramer, & Sawtelle, 2012; Turpen & Finkelstein, 2010). In doing so, many physics education researchers have attended to the contextual aspects of learning physics which stem from disciplinary norms and practices. This era has also seen a spike in demand for students’ computer literacy and technological competency. As such, it has been a growing concern among physics education researchers about how to prepare students for a discipline/world which has become increasingly technological (Cummings, 2011).

Nonetheless, much of what has happened in the PER community since 1998 can simply be described as the timely reaping of that which was sown by physics education researchers in the decades prior. In terms of academic publications, for example, PER was added as a section within *American Journal of Physics* (AJP) in 2005 (Meltzer & Otero, 2015), the *Physics Education Research Conference Proceedings* became a publication of the American Institute of Physics in 2003 (Cummings, 2011), and Robert Beichner established the *Physical Review Special Topics – Physics Education Research* journal (presently named *Physical Review Physics Education Research*) in 2005 (Cummings, 2011). Meltzer and Otero (2015) report that, in AJP and *Physical Review* alone, as many as 50-80 PER publications were routinely produced per year as of 2014. Thus, in the sixty years since the launch of Sputnik, since the curriculum efforts of Arons, Karplus, and Rief, PER has developed into a rich community of researchers investigating how to improve the teaching and learning of physics in a variety of ways.

2.1.2 The topical areas of PER

Having discussed how the academic field of PER came to be, it is now useful for me to briefly discuss the main topical areas that are of interest to the current PER community. Doing so will allow me to illustrate a kind of topical ‘map’ of PER and, subsequently, better position myself in relation to the interests, approaches, and considerations of the broader community of physics education researchers. Several high-quality reviews of PER have been published in recent years (e.g. Beichner, 2009; Cummings, 2011; Russ & Odden, 2018). For the purposes of this section, the most useful among these reviews is Docktor and Mestre’s (2014) synthesis of PER, especially since the authors portray a wide diversity of research topics at a considerable depth of detail. Docktor and Mestre describe PER in terms of six (intersecting) topical areas: (1) conceptual understanding, (2) problem solving, (3) cognitive psychology, (4) assessment, (5) curriculum and instruction, and (6) attitudes and beliefs about learning and teaching. While there are considerable overlaps between many of these topical areas – as well as several unrepresented topical areas such as precollege PER and physics teacher preparation/curricula (admitted by the authors, themselves) – Docktor and Mestre do succeed in synthesizing

much of the existing work on PER within category labels which I believe could be useful as a shared vocabulary among PER scholars.

As I will clarify below, I see my licentiate work as most closely related to (or, perhaps, traversing) the existing work in the first three of Docktor and Mestre's topical areas: namely, conceptual understanding, problem solving, and cognitive psychology. I will first review each of these areas individually and show how my work is situated among them. It is important to note that, while my work relates to these topical areas to a degree, Docktor and Mestre do not, in fact, mention as part of their review *any* of the specific theoretical perspectives which I take in this licentiate thesis. Thus, I will not only show how I relate to each of these three topical areas but also discuss how I go beyond what is mentioned by the authors in their presentation of the PER field. After doing so, for the sake of completeness, I will also briefly review the remaining (latter three) topical areas to delineate the PER efforts to which my work is not closely related.

The relevant PER topical areas for this thesis

Conceptual Understanding

As mentioned above, early PER work was in many ways inspired by the realization that students had difficulties in understanding fundamental physics concepts. As such, the issue of *Conceptual Understanding* is one of PER's earliest and most widely studied topical areas. Researchers have amassed an abundance of documented examples of common student difficulties – around 115 studies on students' "misconceptions" are listed in McDermott and Redish's (1999) resource letter, for instance. Research efforts focused on student difficulties have found that they are generally hard to correct for (Bransford, Brown, & Cocking, 2000; Etkina, Mestre, & O'Donnell, 2005) and that instructional tools which can reliably aid students in overcoming difficulties are generally slow to develop (D. E. Brown & Clement, 1989; Camp & Clement, 1994; Clement, 1993; Sokoloff & Thornton, 1997; Strike & Posner, 1982). For Docktor and Mestre, this type of PER work falls under the subcategory of 'Misconceptions' research.⁸ Importantly, Misconceptions research has led to an increased awareness of specific student difficulties among physics teachers as well as the creation of influential concept inventories like the FCI (see the description of the 'Assessment' topical area below).

A different subset of research within *Conceptual Understanding*, namely 'Ontological Categories' research, is concerned with how student reasoning can be seen to function in terms higher-order knowledge categorizations. These researchers highlight how difficulties with physics tend to arise from

⁸ Though I use it here as a category label, the term "misconceptions" (and to a lesser degree, the terms "alternative conceptions," "preconceptions," or "naïve conceptions") has been routinely criticized by many PER scholars due to its pejorative nature as well as its tendency to convey student difficulties as robust, context-independent packets of knowledge.

students' sorting of scientific ideas into improper knowledge categories (D. E. Brown & Hammer, 2008; Chi, 1992, 1997; Chi & Slotta, 1993; Chi, Slotta, & de Leeuw, 1994; Slotta, Chi, & Joram, 1995). They have found, for example, that student difficulties within the same ontological category are more easily addressed than those between categories (Chi, 2005; Slotta et al., 1995).

Other researchers have shown that, while there may be robust patterns of student responses in particular physics contexts, the architecture of student knowledge might be better approximated as a collection of finer-grained “phenomenological primitives” (p-prims) or “resources” which students leverage on the spot in dynamic ways (diSessa, 1988, 1993; Hammer, 2000; Redish, 2004). This type of PER work falls under the subcategory of ‘Knowledge in Pieces’ research. Typically, ‘Knowledge in Pieces’ researchers have tended to define their work in opposition to (or at least as a necessary nuancing of) the earlier, ‘Misconceptions’ research (diSessa, 1993; Hammer, 1996a, 1996b, 2000; Hammer & Elby, 2002; J. P. Smith, diSessa, & Roschelle, 1994).

For the purposes of this licentiate thesis it is most important to note that, of the three subcategories of *Conceptual Understanding*, my research (esp. Paper III) aligns closest with the ‘Knowledge in Pieces’ research. In part, I concern myself with how students working with physics concepts tend to make (piece together) meaning in terms of smaller, intuition-based chunks of knowledge. To be clear, despite the fact that I share a considerable amount of epistemological ground with both, I explicitly use neither diSessa’s *p-prims* nor Hammer and Redish’s *resources* as the theoretical underpinnings for my research.⁹ Instead, I make use of a different ‘Knowledge as Pieces’ theory called conceptual metaphor (Lakoff & Johnson, 1980), which better relates to my other research concerns of semiotics and language use (see Sections 2.3 and 2.4).

Problem Solving

Another prominent focus of physics education researchers has been within the topical area of *Problem Solving*, no doubt due in part to the central role that problem solving takes in the study and practice of physics.¹⁰ Researchers have investigated how students’ problem solving compares to experts (Bagno & Eylon, 1997; Čančula, Planinšič, & Etkina, 2015; Chi, Feltovich, & Glaser, 1981; Eylon & Reif, 1984; Hardiman, Dufresne, & Mestre, 1989; Larkin, 1981; Larkin, McDermott, Simon, & Simon, 1980; Savelsbergh, de Jong, & Ferguson-Hessler, 2011), how students make use of worked solutions (Chi,

⁹ That is to say that, while neither of these theories of cognition are directly applied in my work, in using another “Knowledge in Pieces” theory (which comes more from research on linguistics), my work still largely aligns with the core commitments of both the p-prims and resources frameworks.

¹⁰ In reading Docktor and Mestre’s review (2014) one gets a sense that the term “problem solving” (whether those problems are highly computational or not) is essentially a descriptor for what might more colloquially be called “*doing physics*.”

Bassok, Lewis, Reimann, & Glaser, 1989; E. Cohen et al., 2008; Ferguson-Hessler & de Jong, 1990; M. Ward & Sweller, 1990; Yerushalmi et al., 2008), how students use mathematics to solve problems (Elaine Cohen & Kanim, 2005; Cui, Rebello, & Bennett, 2006; Nguyen & Meltzer, 2003; Sherin, 1996, 2001), and how instructional strategies can be used to improve students' problem-solving skills (Becerra-Labra, Gras-Martí, & Torregrosa, 2012; Heller & Hollabaugh, 1992; Heller, Keith, & Anderson, 1992; Kortemeyer, Kashy, Benenson, & Bauer, 2008; Lee, Palazzo, Warnakulasooriya, & Pritchard, 2008; Leonard, Dufresne, & Mestre, 1996; Mestre, 2002; Reif & Scott, 1999; Van Heuvelen, 1991c, 1995; Van Heuvelen & Maloney, 1999; Wright & Williams, 1986). Approaches include modeling student's problem solving as abstract, information-processor search operations (Newell, Shaw, & Simon, 1958); examining the effectiveness of students' transfer to new problems from exemplars (Lin & Singh, 2011; Reeves & Weisberg, 1994; Ross, 1987); and exploring the ways that students play "epistemic games" (Tuminaro & Redish, 2007).

One subcategory of *Problem Solving* that Docktor and Mestre discuss – and the strand which I see my work more closely relating to – is the research which they refer to as 'Representations.' In 'Representations' research, scholars tend to be interested in how students make use of representations¹¹ (i.e. those external, typically-visual depictions such as free body diagrams, energy bar charts, and graphs) as they solve physics problems. Perhaps unsurprisingly, researchers have found that the format of representations affects student performance (Kohl & Finkelstein, 2005; Meltzer, 2005). Others have shown that students who draw correct free-body diagrams perform better on problem solving tasks than students who do not draw at all or draw incorrect diagrams (Rosengrant, Van Heuvelen, & Etkina, 2005, 2009). There is a fair amount of overlap between 'Representations' and *Conceptual Understanding*, especially since so many of the fundamental concepts in physics deal with equations and graphs (see, for example, Van Heuvelen, 1991).

In this thesis, I concern myself with how students come to make sense of *semiotic resources* (both disciplinary, mathematical ones and non-disciplinary, conversationally-negotiated ones) in digital learning environments. By semiotic resources, I mean those images, words, artifacts, and behaviors which are used by individuals to make meaning. I am particularly interested in how digital environments make it possible for students to navigate between their physical intuitions, the physical environment, and the mathematical representations used by the physics discipline. In my treatment of the students' use of disciplinary representations, I choose to draw on the theoretical perspectives

¹¹ In this thesis, I will use the term "representation" to refer to external (generally, mathematical) depictions of physics-relevant content. This is especially pertinent since I am interested in how students make meaning with not only the things that would traditionally be called representations (like diagrams and graphs), but also with meaning-bearing systems like spoken language, gesture, touch, and physical apparatus.

of constructionism (Papert, 1980) and a modified extension of Hestenes' modeling framework (diSessa, 1988; Hestenes, 1987) (detailed in Section 2.4).

Cognitive Psychology

The last relevant topical area of PER from Docktor and Mestre – which, while being less widespread than either of the previously discussed areas, also shares a considerable amount of overlap with both – is the category of *Cognitive Psychology* research. This topical area generally involves the borrowing of methodologies from cognitive psychology for application in physics education settings. Researchers within the *Cognitive Psychology* area of PER have studied how physics knowledge activation depends on framing and context (Dufresne, Mestre, Thaden-Koch, Gerace, & Leonard, 2005; Hammer, Elby, Scherr, & Redish, 2005; Redish, 2004), how students' physics knowledge can be bound to particular examples (Bassok & Holyoak, 1989; Reeves & Weisberg, 1994; Ross, 1984, 1987, 1989), and how students' attention is directed within diagrams and during problem solving¹² (Carmichael et al., 2010; Feil & Mestre, 2010; Graesser, Lu, Olde, Cooper-Pye, & Whitten, 2005; Kozhevnikov, Motes, & Hegarty, 2007; Madsen, Larson, Loschky, & Rebello, 2012; Rosengrant, Thomson, et al., 2009; A. D. Smith, Mestre, & Ross, 2010; van Gog, Paas, & Van Merriënboer, 2005). These research efforts tend place less emphasis on developing instructional strategies, instead focusing on how students' cognitive processes (or, at least, observable proxies for cognitive processes) change in response to various contexts.

Docktor and Mestre identify two other strands within *Cognitive Psychology* that I find relevant to my licentiate work. The first of these is the subcategory of 'Analogical Reasoning,' which includes those researchers who examine the roles that analogies play in students' reasoning (Haglund, 2017; Podolefsky & Finkelstein, 2006, 2007b, 2007a). Since I have concerned myself with students' self-directed conversational interactions, I draw from existing work on students' self-generated analogies (e.g. Dudley-Marling & Searle, 1995; Enghag, Gustafsson, & Jonsson, 2009; Enghag & Niedderer, 2008; Haglund & Jeppsson, 2012; Heywood & Parker, 1997; Milner-Bolotin, 2001). Furthermore, as mentioned in the section on *Conceptual Understanding* above, I make use of theoretical perspective called conceptual metaphor, which posits that reasoning processes are analogically related to 'chunks' of cognition gleaned from physical experiences.

The second relevant subcategory of *Cognitive Psychology* that Docktor and

¹² It is important to distinguish this subcategory of "attention" work (largely associated with eye-tracking) from the work done on disciplinary discernment and awareness in physics learning from Variation Theory (e.g. Eriksson, Linder, Airey, & Redfors, 2014; Fredlund, 2015; Fredlund, Airey, et al., 2015; Marton & Booth, 1997). The latter perspective is one which I plan to incorporate it in my future research (see Chapter 8).

Mestre identify in PER is research on ‘Language.’¹³ Research in this area has investigated, for example, how the seemingly subtle changes in the words used to refer to a concept (e.g. using “heating” instead of “heat”) can affect students’ conceptual understanding (e.g. Brookes & Etkina, 2015). Other theoretical frameworks such as systemic functional linguistics have been used to examine the importance of grammar and word choice in physics teaching and learning (e.g. Brookes & Etkina, 2007, 2009, 2015). As the *Cognitive Psychology* topical area is the sole place in which Docktor and Mestre mention research on language across all of PER, it is worth briefly describing my treatment of language here (as well as my departure from the kind of work the authors describe in this topical area).

In this thesis, I approach the topic of language and communication from the perspective of social semiotics (e.g. Airey & Linder, 2017; Tobias Fredlund, 2015; Tobias Fredlund, Linder, & Airey, 2015). In doing so, I choose to view the language used by students (and the discipline of physics) as the socially-valenced activity of communication. Of paramount importance is the process of individuals’ meaning making, wherein I examine not only on the spoken and written words used by students but also on other communicational modalities such as gesture, gaze, body position, and haptic-touch (again, see Section 2.4 for a full discussion of this theory).

The topical areas this thesis (largely) avoids

For the purposes of explaining the type of PER work that this licentiate thesis is *not*, I now give a brief summary of the remaining topical areas from Docktor and Mestre’s review. It is worthwhile to reiterate that beyond these topical areas described by Docktor and Mestre, there is a significant amount of research done in physics teacher preparation and pre-college PER to which I also do not directly relate.

Curriculum and Instruction

Physics education researchers have consistently contributed to the development and study of various physics curricular tools/interventions. The most prolific of these might be the interactive engagement curricula that encourage students’ active involvement during lectures (Beatty, Gerace, Leonard, & Dufresne, 2006; Ding, Reay, Lee, & Bao, 2009; Dufresne, Gerace, Leonard, Mestre, & Wenk, 1996; Keller et al., 2007; Mazur, 1997). Other well-studied and PER-informed curricula include *Interactive Lecture Demonstrations* (Sokoloff & Thornton, 2004), *Just in Time Teaching* (Novak, Patterson, Gavrin, & Christian, 1999), the University of Washington’s widely-adopted *Tutorials in Introductory Physics* (McDermott et al., 1998), problem-based

¹³ Note that here, Docktor and Mestre’s version of ‘Language’ is not the best fit for the type of work I do in this licentiate thesis. As mentioned in Chapter 1, I see myself investigating the role of language in terms of social semiotics, embodied cognition, and conversation analysis, which Docktor and Mestre miss altogether in this subcategory.

learning (Dutch, Groh, & Allen, 2001), *Physics by Inquiry* (McDermott, Shaffer, & Rosenquist, 1996a; McDermott et al., 1996b), *Workshop Physics* (Laws, 1991), *Studio Physics* (Cummings, Marx, Thornton, & Kuhl, 1999; J. M. Wilson, 1994), SCALE-UP Physics (Beichner et al., 2007), and the *Technology-Enabled Active Learning* project from MIT (Dori et al., 2003). In the laboratory, curricula such as *RealTime Physics* (Sokoloff, Laws, & Thornton, 2007) have been designed to include microcomputer-based sensors (see Sec. 2.2) and the *Investigative Science Learning Environment* labs (Etkina et al., 2010; Etkina, Van Heuvelen, et al., 2006; Etkina & Van Heuvelen, 2007) have been designed to engage students in the processes resembling authentic science practice. As much of PER is eventually aimed at improving the physics classroom, all (if not, most) PER scholars should perhaps not only be aware of the curricular tools produced by the PER community but also remain cognizant of how each of their research efforts might be operationalized inside and outside the classroom. Doing so allows one to answer the ‘so what?’ question for physics teachers and students. Nonetheless, though I hope that the research in this thesis might be used to inform the design of future curricular tools or strategies, this is not the immediate focus of my work.

Assessment

As the catalog of documented student difficulties has grown (see *Conceptual Understanding*, above), so too has the capability to develop and validate assessment tools which probe conceptual understanding. Early PER assessment tools included the FCI (Hestenes et al., 1992), Mechanics Baseline Test (Hestenes & Wells, 1992), and the Test of Understanding Graphs in Kinematics (Beichner, 1994). As of 2014, Docktor and Mestre report that more than 30 concept inventories exist for the topics of kinematics/mechanics (Beichner, 1994; Halloun & Hestenes, 1985; Hestenes & Wells, 1992; Hestenes et al., 1992; Nieminen, Savinainen, & Viiri, 2010; Rosenblatt & Heckler, 2011; Thornton & Sokoloff, 1998), electricity and magnetism (Chasteen, Pepper, Caballero, Pollock, & Perkins, 2012; Ding, Chabay, Sherwood, & Beichner, 2006; Engelhardt & Beichner, 2004), quantum mechanics (McKagan, Perkins, & Wieman, 2010), energy (C. Singh & Rosengrant, 2003), and scientific reasoning more generally (Lawson, 1978).¹⁴ Among many other things, assessment tools in PER have had a major impact on the trustworthiness of the field of PER, especially in communicating with physics-department colleagues who are accustomed to quantitative data. However, as I will discuss in Chapter 4, I have chosen to use qualitative methods in this thesis to look at the moment-to-moment interactions of students. Thus, I take a methodological position which is different from those commonly taken in this topical area.

¹⁴ For those interested, a more complete collection of these tests can be found online at the PhysPort website (<https://www.physport.org/assessments/>).

Attitudes and Beliefs about Teaching and Learning

Physics students and teachers bring with them attitudes and beliefs about learning physics which are certainly salient for physics teaching and learning. Earlier work by Hammer (1989, 1994, 1995, 1996a), Linder (1993), and Elby (1999) developed into theories of teachers' and students' epistemological beliefs in physics, which has led to the design of several survey tools for measuring attitudes and beliefs (Adams et al., 2006; Gaffney, Gaffney, & Beichner, 2010; Halloun, 1997; Redish, Saul, & Steinberg, 1998; White, Elby, Fredericksen, & Schwarz, 1999). With teachers, Henderson and Dancy (2007, 2009) have done significant work to examine how faculty perceive their own (and others') practice. Nonetheless, my focus on students' reasoning processes during small-group interactions means that I have left this topical area of attitudes and beliefs largely untouched.

2.1.3 My position in the Docktor-Mestre map of PER

Having reviewed the breadth of interests and projects in PER, it is worthwhile to now summarize how I see my work positioned within Docktor and Mestre's map of PER. The first important feature of this thesis is that I am focused on bringing together (and generating) *theoretical* perspectives, especially as tools through which one might better understand students' meaning making around digital learning environments for physics. Theory work in PER is relatively uncommon, especially as compared to the vast amounts of work devoted to developing instructional tools and probing students' conceptual understanding (Johansson, 2018, p. 28). Thus, in my emphasis on theory— a focus which, to an extent, I defend in Chapter 4 – I can position myself among much of the existing PER literature.

Furthermore, while I see myself uniquely contributing to each of the PER areas of *Conceptual Understanding*, *Problem Solving*, and *Cognitive Psychology* alike (from Doctor and Mestre, which I have described above), I aim to contribute moreover by simultaneously working across all three. To be clear, in my novel use of the conceptual metaphor perspective, I see myself contributing to (and going beyond) the 'Knowledge in Pieces' subcategory of *Conceptual Understanding* and the 'Analogical Reasoning' subcategory of *Cognitive Psychology*. Similarly, in my incorporation of constructionism and semi-formal modeling, I see myself contributing to (and going beyond) the literature within the 'Representations' subcategory of *Problem Solving*. In my particular use of multimodal social semiotics, I include a subfield of research on language which Docktor and Mestre avoid completely.¹⁵ In each of these ways, and for each of these topical areas, I see my work as a worthwhile and novel contribution. Still, it is especially in dealing with all of these

¹⁵ While I have only introduced each of these theoretical perspectives briefly so far, I will cover each one in depth in Sec. 2.4.

perspectives *together* that I hope to bring new research insights to the PER community.

Another unique aspect of the work done in this thesis is in my focus on instructional technology (IT) – in particular, my focus on digitally-supported learning environments that have yet to be thoroughly explored and documented. To adequately discuss this point, I now review the work done in PER around IT and further position myself in relation to the existing PER-relevant IT research.

2.2 Instructional technology in PER

Mentioning ‘digital technology’ can tend to imply a contemporaneity with our current culture – that is to say, perhaps, that digital technology is more of a modern-day *zeitgeist* than a mid-twentieth-century one. Thus, it might seem reasonable to the younger, tech-savvy person today that the study of digital technology in education is a relatively untapped, modern area of investigation. However, such a notion misses the fact that, to a large extent, the field of PER grew up alongside modern computers.¹⁶ In reality, since the science curriculum development projects of the 1950s and 1960s, there has been a consistent – albeit minority – focus on the role of digital technology in the teaching and learning of physics. In this section, I will review the PER work done in the area of instructional technology (which I refer to as PER-IT) accumulated in the past sixty years and reflect on how this licentiate thesis is positioned in relation to this body of research. To the best of my knowledge, a current review of technology in PER (in the detail of other PER reviews such as Beichner, 2009; Cummings, 2011; Docktor & Mestre, 2014; McDermott & Redish, 1999; or Meltzer & Thornton, 2012) has not yet been completed. Thus, in addition to providing some context for the research in this thesis, I hope this section might also serve as a kind of reference for other PER scholars interested in the role of technology in the teaching and learning of physics.

2.2.1 The paradigmatic development of PER-IT

As I did with PER in the preceding section, I will begin by reviewing the historical development of PER-IT. To do so, I will take inspiration from Koschmann’s (1996) review of general IT, which casts the development of IT as a series of progressive revolutions through scientific paradigms.¹⁷ Koschmann describes four key paradigms in IT research, namely (1) Computer-Assisted

¹⁶ Many see the first ‘personal computers’ – i.e. computers that were designed for a single person, were easy to use, and were cheap enough for an individual to buy (Allan, 2001) – as having arrived sometime in the 1970s. As discussed in Sec. 2.1, modern PER came about in the 1970s as well.

¹⁷ As an application of Kuhn’s (1970) work on the nature of scientific revolutions.

Instruction, (2) Intelligent Tutoring Systems, (3) Logo-as-Latin, and (4) Computer-Supported Collaborative Learning. Each of these paradigm can be seen as a ‘revolutionary’ departure from the decade of IT research which preceded it, marking a fracture in the community of IT researchers around issues of “terminology, conceptual frameworks, and views on what constitutes the legitimate questions of science” (Koschmann, 1996, p. 2). It is important to note that in the Kuhnian view of paradigms, the emergence of each new paradigm does not signal the death of the old one. In Koschmann’s description of IT, for example, the emergence of the second, Intelligent Tutoring Systems, paradigm does not mean that the Computer-Assisted Instruction paradigm ceased to garner any attention. Instead, each paradigmatic shift marks the emergence of a new branch of IT work which runs parallel to the existing branches.

In adapting Koschmann’s description of IT-in-general for my focus on physics, I have devised three PER-IT paradigms: (1) Computer-Assisted Instruction, (2) Computer Constructivism, and (3) Computer-Supported Collaborative Learning. As I will discuss below, my departure from Koschmann’s paradigms was inspired by the fact that some of the paradigmatically-salient occurrences that affected IT-in-general had less of an impact within the PER community. Likewise, in conceptualizing the second (Computer Constructivism) paradigm of PER-IT, unique developments of technology tailored for physics as a discipline (i.e. physics’ emphasis on computational problem solving and laboratory work) led me to conceive a paradigm which was largely absent from the broader field of IT. It is also worth mentioning that the efforts around the development of PER-IT I discuss below were as much the result of the chronological progression of technological advances as they were the engine reflexively directing the development of future technology. Though we have seen advancements in learning theories and models of cognition enter the focus of educational researchers in the last few decades of the 20th century, advancements in the technology itself gave the theoretical commitments of each paradigm the feasibility to thrive within IT research.

1957: Computer-Assisted Instruction

If, by a miracle of mechanical ingenuity, a book could be so arranged that only to him who had done what was directed on page one would page two become visible, and so on, much that now requires personal instruction could be managed by print.

(Thorndike, 1912, p. 165)

In late-1950s America, the inclusion of technological innovations like the computer in physics education reform efforts was perhaps an obvious choice for curriculum developers, especially after the watershed launch of Sputnik in 1957 had ostensibly called into question America’s technological capability

(Cummings, 2011; Meltzer & Otero, 2015). Soon after the Soviet satellite was sent into orbit, several universities began developing computer-based curricular materials for science and engineering education (Schwarz, Kromhout, & Edwards, 1969). For example, in 1959 researchers at the University of Illinois founded the influential PLATO project for the “exploration of the educational possibilities [...] relating to the introduction of the modern high-speed computer as an active element in the instructional process” (Alpert & Bitzer, 1970).¹⁸ By 1961, researchers at the University of Michigan had developed an entire “programmed instruction” physics curriculum which included carefully planned sequences of computer-based physics problems (Orear, 1962). These efforts and many that followed were originally focused on using the computer as a tool for structured drill and practice. As such, computer-based curriculum developers lauded how their programs allowed each student to proceed through mathematical exercises at their own pace with immediate feedback from the computer.

By the second half of the 1960s, the burgeoning field of research into computers in physics instruction had developed enough critical mass to merit its own national conferences and academic journals dedicated to the topical area. In 1965, the Commission on College Physics sponsored both the *Conference on New Instructional Materials in Physics* (Commission on College Physics, 1965) and the *Conference on the Uses of the Computer in Undergraduate Physics Instruction* (Commission on College Physics, 1965). In 1966, the *Educational Technology* journal was founded (JSTOR, 2019). By 1969, as many as 27 significant research projects were taking place across the U.S. on the topic of computer-assisted instruction in physics (Schwarz et al., 1969). Other non-American efforts include Computer-Aided Teaching of Applied Mathematics at Cambridge University (Harding, 1974, 1976).

Efforts to include computers in physics education which took place in this era – that is, in the period starting from the launch of Sputnik and lasting through the mid-1970s – largely fit within a paradigm which I will refer to as Computer-Assisted Instruction (CAI).¹⁹ As will become apparent in my discussion of the other paradigms in PER-IT, the CAI paradigm was in many ways a product of the available computing technology at the time. Researchers

¹⁸ The PLATO (Programmed Logic for Automatic Teaching Operations) project would produce a series of computer-based learning systems from 1960 to 1994, during which time the project eventually worked to “dispel the notion that computer-assisted instruction was limited to [such rote learning situations as arithmetic drill and practice]” (Alpert & Bitzer, 1970, p. 1584). One key innovation of the PLATO educational systems were their initial inclusion of TV displays (screens) for displaying non-text information (Bitzer & Braunfeld, 1962).

¹⁹ In his discussion of the paradigmatic shifts of IT research, Koschmann (1996) splits the 1960s and 1970s into two separate paradigms, namely Computer-Assisted Instruction (CAI) and Intelligent Tutoring Systems (ITS), respectively. However, as it seems that the physics community did not see the level of immigration from the field of artificial intelligence research as did IT research in general, physics-specific-IT research did not undergo the same ITS paradigm revolution. Thus, I have chosen to describe the period from 1957 to the mid-1970s as a single, CAI paradigm inspired by Koschmann’s CAI paradigm for the 1960s.

in this era were spurred on by the advent of the transistor, the integrated circuit, and (subsequently) time-shared computing.²⁰ As such, the computers which were available to CAI researchers were a stark departure from the sluggish, vacuum tube computers of before. An early pioneer in IT research from MIT, Cynthia Solomon, explains,

[Time-shared computing] was a step toward personal computing. The goal of time-sharing was to bring people into immediate and intimate contact with computing. Although the key to time-sharing was the sharing of the computer among as large a community of users as possible, the user was to feel a direct and personal relationship with the machine. Typewriter terminals replaced punched cards as the standard mode of communication between human and machine. Feedback from the computer was presented in seconds rather than in hours or days.

(Solomon, 1986, p. 6)

Time-shared computing allowed for individual students to interact with computers via typewriters such that – so long as the processing demand of each student was kept low – whole classrooms of students could have a one-on-one interaction with a computer mainframe.

For the CAI paradigm, these technological steps toward personalization of the computer were paired with another defining aspect of the paradigm: the prevailing transmissionist/behaviorist learning theories popular at the time among physics educators (Arons, 1998; Koschmann, 1996). The underlying philosophy of much of the CAI development was that the computer should act as an artificially intelligent, responsive textbook or tutor. Dialogs were programmed to take place between each student and the mainframe computer wherein a student could respond to a series of questions and prompts via a typewriter interface (eventually, students were also able to respond to computers via other interface devices such as light pens on cathode-ray tube displays, see Alpert & Bitzer, 1970; Bitzer & Braunfeld, 1962; Buck & Hunka, 1995; Schwarz et al., 1969; Zinn, 1967). For example, by the early 1970s, the CONDUIT project was established as a resource bank of these tutoring dialogs which were tested against various criteria (Peters, 1980; United States Congress Office of Technology Assessment, 1982). Thus, while even the best-spoken lecturer or most well-written textbook had the difficult task of catering to whole rooms of students simultaneously, time-shared computers allowed for each student to have an individualized instructional experience along a structured sequence of content. In this way, it was hoped that each student would learn the teacher's predetermined content at their own pace and with

²⁰ The transistor and integrated circuit both marked sizeable leaps in the speed and reductions in size of computers at the time. Time-shared computing soon followed, which involved several typewriter terminals connected to a single mainframe computer in a manner such that individual users could interact with a single machine simultaneously.

constant feedback on their understanding (à la *operant conditioning*)²¹ via a channel of “student-computer dialog” (Bork & Sherman, 1971, p. 137).

Nonetheless, this is not to say that all work during this time was focused on structured dialogs. In fact, it was generally accepted by many researchers at the time that the computer could take on a variety of roles in the science classroom (Blum & Bork, 1970; Bork, 1979; Hinton, 1978; Schwarz et al., 1969; Zinn, 1967). It was during the CAI-paradigm era that the many of the later-dominant modes of computer use were first implemented. Alfred M. Bork, who was perhaps the most prolific physics education reformer within the CAI-paradigm era, wrote this with Ronald Blum about the role of the computer in the physics classroom:

In discussing the use of the computer [in education], we can distinguish at least five modes of usage, each embracing several types of output: alphanumeric or graphic, paper or film, temporary or permanent. The five modes are (1) producer, (2) administrator, (3) tutor, (4) simulator, and (5) calculator, listed roughly in order of increasing demands on the students’ understanding and participation.

(Blum & Bork, 1970, p. 963)

For Bork and Blum, computer usage in the “producer” mode involved the creation of films (i.e. frame-by-frame graphs), illustrations, and textbook writing/creation. The “administrator” mode entailed giving students exams, grading student work, providing students with course information, etc. The “tutor” mode involved the dialogs discussed above. The “simulator” mode involved students inputting values into a program and receiving the output of the system (i.e. a position vs. time graph of a damped harmonic oscillator based on specified initial conditions) (e.g. Bork & Robson, 1972; Bron, 1972; Stannard, 1970). Finally, the “calculator” mode entailed students solving physics problems via programming in lower-level computer languages like BASIC and FORTRAN (e.g. Bork, 1964, 1967, 1968, 1970, 1973, Harding, 1974, 1976).

However, while the foresight for these various modes of computer usage was fast to emerge during the CAI-paradigm era, the viability of the latter two of Blum and Bork’s computer modes in particular, “simulator” and “calculator,” increased drastically after the advent of the microprocessor and its inclusion into next generation computers. Both of these uses of the computer (and more) were central to the revolutionary work of the next paradigm in physics-related IT, which I call Computer Constructivism (see Figure 2).

²¹ As a matter of no coincidence at all, some of the early CAI systems were heavily inspired by B. F. Skinner’s vision for mechanical teaching machines (e.g. Skinner, 1958). In fact, during their early forays into IT, IBM worked with Skinner on developing a prototype of one of his teaching machines in their Electric Typewriter Division in the 1950s (Buck & Hunka, 1995).

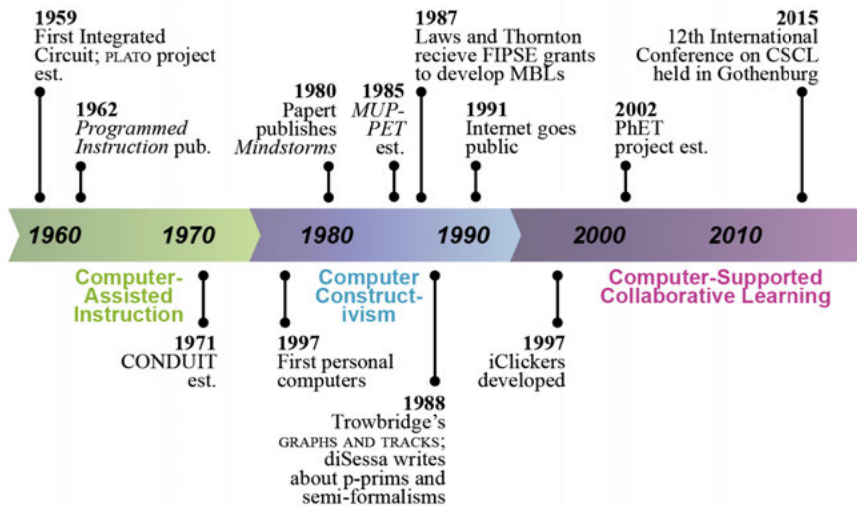


Figure 2. A timeline of the paradigmatic development of PER-IT inspired by Koschmann (1996).

Mid-1970s: Computer Constructivism

Solving a mathematical problem is a process of construction. The activity of programming a computer is uniquely well suited to transmitting this idea.
(Feurzeig, Papert, Bloom, Grant, & Solomon, 1969, p. 14)

Following the advent of the microprocessor in 1971, the prospect of time-sharing as the dominant configuration for computers in the classroom was soon “dead” (Solomon, 1986, p. 7). By 1977, personal computers became available and, with them, teachers saw a marked increase in the computing power at the disposal of each student. Time-shared computing had required that low-demand packages be used by each individual typewriter terminal so as to not collectively overburden the single mainframe machine at their nexus. Now instead, microcomputing allowed each student to have access to an expanded computational head room wherein higher-level programming languages could be used and more complex packages could be run (including graphics-heavy programs).

Among the first to take advantage of this technological revolution were a team of researchers, Wally Feurzeig, Seymour Papert, and Cynthia Solomon, from Bolt, Beranek and Newman (BBN) in Cambridge, Massachusetts. Starting in 1967, this BBN-based team had been exploring the idea of computers as mathematically-rich environments in which young students could playfully construct systems of their own. As a result, they developed the hugely

influential educational programming language called Logo. Though the original development of the Logo language had taken place before personal computers, it was the microprocessor revolution which made it feasible for Logo – a higher-level language that would have been seen as too demanding for most time-shared computing – to be implemented at scale. In 1980, Seymour Papert published, *Mindstorms*, a provocative book in which he envisioned the educational potential of computer programs such as Logo in the future education of mathematics and science students. Papert, who was a South-African-born mathematician and protégé of Piaget in Geneva from 1958 to 1963 (MIT, 2007), devised the constructionism theory of learning, based around personal computer use and constructivism.²² In this view, students were asked to design, build, and debug computer programs in order to become more fluent in the systematicity inherent in computers’ infrastructure. Though his work is not frequently cited in PER today, Papert’s early attention to educational technology has had a lasting impact on modern PER.²³

Around the same time, with PER now well in the “Early Years” of its development (Cummings, 2011) (see Section 2.1), early physics education researchers took advantage of the capabilities of personal computers in other ways. In 1983, Edward Redish and Jack M. Wilson started the Maryland Project in Physics and Educational Technology (MUPPET) to introduce introductory physics students to computational programming at the start of their traditional calculus-based course (Redish & Wilson, 1993, p. 222). Projects like MUPPET made use of the computational power of the computer to introduce mathematically-complex concepts earlier in a student’s career than would normally be permitted from their mathematical proficiency. As Redish and Wilson explain,

The primary constraint that has kept the profession from introducing more creative science at an early stage is the limited mathematical ability of the introductory student. Creative and open-ended problems using analytical tools require a level of mathematical sophistication not usually obtained by students until their third year of college. In the past decade, however, there has been an immense growth in the power and availability of computer tools and technology. More power is packed into a desktop computer the size of a breadbox than was available in mainframes 30 years ago. Programming environments have been transformed from complex line editing with batch compiling in FORTRAN

²² The Logo programming language and constructionism were massively influential in IT, so much so that Koschmann describes the IT paradigm of the 1980s as “Logo-as-Latin.” Koschmann chooses this name because the students’ use of programming languages like Logo was meant to serve them generally across diverse educational objectives (Koschmann, 1996, 1997). However, within physics education there were other uses constructionism-influenced implementations of IT – with computational programming and with microcomputer-based laboratory tools – so I see it worthwhile to depart from Koschmann’s label.

²³ Michael Wittmann’s “PER Family Tree” lists Papert as the mentorship progenitor for the branch containing such scholars as Andy diSessa, David Hammer, Barbara White, Bruce Sherin, Noah Finkelstein, Rosemary Russ, and Ayush Gupta, among others (Wittmann, 2008).

to systems with full-screen editors, fast compilers, and interactive debuggers in unified, easy-to use- environments in PASCAL, C and structured BASIC. These developments open the possibility that students could be given the computer power to solve more interesting problems in the introductory course with little training.

(Redish & Wilson, 1993, p. 223)

To a degree, the computational programming efforts of this era were the realization of the programming-rich introductory physics courses which Alfred Bork had envisioned in the 1960s (e.g. Bork, 1964, 1968), newly made possible by the rapid growth of computing capability of the microprocessor.

At the same time that personal computers became more feasible machines for creative and computational programming, the microprocessor allowed for the creation of computer-based tools which could be used as sensors in the physics laboratory. Working with Rob Tinker at the Technical Education Research Center (TERC) in Cambridge, Massachusetts (Tinker, 1981), Ronald Thornton began developing microcomputer-based laboratory (MBL) tools in 1983 for physics experiments in middle school science classrooms (Laws et al., 2015). By 1986, MBL tools began being adapted for college-level laboratory work by Thornton, David Sokoloff, and Priscilla Laws across several simultaneous projects (Cummings, 2011; Laws et al., 2015). Motivated by the evidence mounting from PER on the unproductiveness of lecture-based physics teaching, these efforts produced innovative IT-rich curricula like *Workshop Physics* (Laws, 1991) and *Tools for Scientific Thinking* (Thornton, 1987).

MBL instruments [...] give the science learner unprecedented power to explore, measure and learn from the physical world. [...] [They] make use of inexpensive microcomputer-connected probes to measure such physical quantities as temperature, position, velocity, acceleration, sound, light, force and physiological indicators such as heart rate. Measurements taken by the probes are displayed in digital and graphical form as the measurement is taken. Data can also be transformed and analysed, printed or saved on to discs for later analysis. Carefully developed software makes these laboratory tools easy to use, even for the first time. MBL tools dictate neither what is to be investigated nor the steps of an investigation. Consequently, students feel in control of their own learning. Moreover, these general tools can be used with many different curricula by both physics majors and non-majors.

(Thornton, 1987, p. 232)

In a manner unique to the needs and interests of physicists, MBL tools were crafted to give students new access to features of the physical world and the mathematical formalisms which the discipline of physics uses to describe them.

I refer to the efforts of researchers and developers from the mid 1970s through the early 1990s – that is, the Logo constructionism, MUPPET-style computational programming, and MBL-infused curricula discussed above –

as the collective paradigm of Computer Constructivism (CC) (see Figure 2). Researchers were making use of the insights of the constructivism perspective on learning – which at this time had all but replaced the transmissionist perspectives of many physics educators in the decades prior – alongside a micro-processor-fueled revolution in computing power. Especially in relation to the previous CAI paradigm, it is important to note how CC efforts in PER-IT were no longer emphasizing the need of the computer to be a delivery system of carefully curated content. Instead, IT-interested researchers within the CC paradigm saw the value of allowing students to create computer-based worlds, program mathematical solutions, and explore the physical world for themselves.

Mid-1990s: Computer-Supported Collaborative Learning

In the 1990s, as the emergence of the public Internet showed the potential for technology to bring people together in revolutionary ways, and as some researchers reacted against the software which tended to isolate individuals from one another, a new movement emerged within IT research to investigate the collaboration of students during technology-supported learning (Stahl, Koschmann, & Suthers, 2006). Much of this movement would eventually rally under the banner of Computer-Supported Collaborative Learning (CSCL), sometime after an international workshop in Maratea, Italy first used the phrase in its title in 1989 (Koschmann, 1996; Stahl et al., 2006). As Stahl, Koschmann, and Suthers explain,

Within CSCL, the focus of learning is on learning through collaboration with other students rather than directly from the teacher. Therefore, the role of the computer shifts from providing instruction—either in the form of facts in computer-aided instruction or in the form of feedback from intelligent tutoring systems—to supporting collaboration by providing media of communication and scaffolding for productive student interaction.

(2006, p. 6)

This emphasis on collaborative technology coincided with the growing popularity of socio-cultural/social constructivist and situated cognition learning theories – i.e. Vygotsky (1986; 1978), Lave and Wenger (1991), Cole and Engeström (1993), and Brown Collins and Duguid (1989), etc. – both within PER and also more broadly in science education research across the western world (De Jong, 2007). Since 1995, an international CSCL conference has been held biannually. In 2005, the *International Journal of Computer-Supported Collaborative Learning* was founded (Stahl et al., 2006).

CSCL efforts tend to fall into two camps: (1) where the computer provides the channels of communication (e.g. email, chat, discussion forums, videoconferencing, etc.) through which students interact and (2) where the computer meaningfully scaffolds interactions between students in person. Within the former camp, PER work has mostly been characterized by investigating the

effectiveness of MOOCs (Massive Open Online Courses) (e.g. Dubson, Johnsen, Lieberman, Olsen, & Finkelsteins, 2014). Within the latter camp, that is where the computer supports in person interaction, PER work has focused on how small student groups work with and around digital technology like interactive whiteboards (e.g. Gregorcic, 2015b; Gregorcic, Etkina, & Planinsic, 2017; Gregorcic & Haglund, 2018) or infrared cameras (Samuelsson, Elmgren, & Haglund, 2019).

However, while there has certainly been a growing number of physics education researchers investigating PER-IT with socially-cognizant frameworks (and/or with an emphasis on students' collaboration), the established category label of CSCL research is scarcely used in the PER community at all. I use "CSCL" here to designate the paradigm which I view as a departure from the CC paradigm, despite the term not being common parlance for most physics education researchers. Perhaps, as Koschmann suggests in his paradigmatic review of general IT, there remains a question of whether or not CSCL constitutes a new paradigm for research in IT (Koschmann, 1996). Or perhaps still, since this era has seen a significant amount of other PER-IT work that better aligns with either the CAI or CC paradigms than with CSCL, it has become increasingly difficult to notice the CSCL work as separate from those existing efforts. For example, computer problem-solving coaches (Hsu & Heller, 2005; Kane & Sherwood, 1980; Reif & Scott, 1999; Ryan, Frodermann, Heller, Hsu, & Aryal, 2014; Sherwood, 1971; S. G. Smith & Sherwood, 1976) and web-based homework programs like Mastering Physics are examples of recent CAI-paradigm work (Bonham, Deardorff, & Beichner, 2003; Cheng, Thacker, Cardenas, & Crouch, 2004; Kashy et al., 1993, 1995; Kortemeyer et al., 2008; Lee et al., 2008; Pascarella, 2002). *Physlets* (Christian & Belloni, 2001; Dancy, Christian, & Belloni, 2002) and the widely-used PhET simulations (Adams, Paulson, et al., 2008; Adams, Reid, LeMaster, et al., 2008; Adams, Armstrong, & Galovich, 2015; Perkins et al., 2006; Wieman, Adams, Loeblein, & Perkins, 2010; Wieman, Adams, & Perkins, 2008) are examples of modern CC-paradigm work which has developed since the 1990s. Regardless, especially as I see this thesis as aligning with CSCL, I contend that the CSCL paradigm is a relevant subset of PER-IT work which highlights the ways in which digital technology can facilitate and augment the collaborative learning of physics content. Having reviewed the historical development of IT in PER (see Table 1 for a summary), it is now worthwhile to review the existing areas of research which incorporate IT as a main focus.

Table 1. A summary of the PER-IT paradigms.

Paradigm	Theory of Learning (learning is...)	Role of Technology (technology should...)	Technological innovations (technology is...)
Computer-Assisted Instruction (1957 to mid-70s)	acquisition of knowledge with quick, corrective feedback (Behaviorism)	act as <i>teacher/tutor</i> , sharing content efficiently and determining if students have learned what is shared	transistors, integrated circuits, mainframe computers, time-shared computing, typewriter terminals
Computer Constructivism (mid-70s to early 90s)	active construction of new knowledge (Constructivism)	act as a <i>systematic environment</i> , allowing students to build worlds and calculate; also, act as a <i>sensor</i> for probing the physical world	microprocessors, personal computers, microcomputer sensors
Computer-Supported Collaborative Learning (early 90s onward)	activity in social contexts (Social Constructivism and Situated Cognition)	act as <i>facilitator</i> of the interpersonal act of learning among students and teachers	internet, smartphones, large touchscreens, haptic feedback, virtual reality

2.2.2 The topical areas of PER-IT

As I did with PER in Section 2.1.2, I will now provide a brief review of the topical areas which span much of the work done in PER-IT. The topical areas which I have identified are, namely, (1) controllable worlds, (2) human-computer interfaces, (3) microcomputer-based laboratory tools, (4) programming, (5) student response systems, (6) tutors and video, and (7) distance learning.²⁴ I begin by discussing the first two of these areas, to which I see myself more directly contributing in this thesis. Then, I will briefly review the remaining areas of PER-IT within which I do not see myself working.

Topical areas of PER-IT to which this thesis contributes²⁵

Controllable Worlds: Simulations, Microworlds, and Games^{II}

As I discussed above, computers have long been used as an instructional tool to run virtual physics experiments wherein a simulated environment responds to student-controlled inputs. As these virtual learning environments bear a striking

²⁴ The topical areas which I list here are my attempt to synthesis and update similar reviews of computer-use in physics teaching and learning made by Blum and Bork (1970), Bork (1981), Schwarz et al. (1969), Wilson and Redish (1989) and Redish (1993).

²⁵ As a reminder, the superscript roman numerals found here and throughout the remainder of this thesis are used to denote instances where portions of the section that follow were originally written in Paper I, II and III (see the ‘Notes for the reader’ section before Chapter 1).

similarity to the computational simulations used by physicists to treat analytically-elusive phenomena, they are often referred to as *simulations*.²⁶ The earliest PER-based curricula built around computer simulations was likely Trowbridge's GRAPHS AND TRACKS instructional software from the 1980s (McDermott, 1990; Meltzer & Thornton, 2012), though computer-based physics simulations intended for education had emerged much earlier in the early computer efforts of physics education reformers in the 1960s (Commission on College Physics, 1965; Luehrmann, 1967; Schwarz et al., 1969).

Arguably the most widely-used, PER-based collection of physics learning simulations are the PhET (Physics Educational Technology) Interactive Simulations out of the University of Colorado Boulder. Since the project's founding in 2002, these web-based simulations have been designed to have a "PhET Look and Feel" – which includes features such as intuitive controls, 'correct' visual representations of physics models, everyday objects and situations, etc. – developed through extensive feedback from student interviews (Adams, Reid, Lemaster, et al., 2008b, 2008a). Recently, the PhET team has put an emphasis on developing their simulations to be accessible (Morgan & Moore, 2016; Perkins & Moore, 2017) and PhET-iO has been developed to data-log students use of the software (López-Tavares, Perkins, Reid, Kauzmann, & Aguirre-Vélez, 2018). Other notable physics simulation software include *Physlets* (Christian & Belloni, 2001) and *GeoGebra* (Arnone, Moauro, & Siccardi, 2017; Hohenwarter & Fuchs, 2004; Lingefjård & Ghosh, 2016).

In line with the *Conceptual Understanding* area of PER (Section 2.1.2), simulations have been valued as a source for the 'discrepant events' which compel students to reconcile their own (incorrect) conceptions with the observable events in the simulation (Tao & Gunstone, 1999; Zacharia & Anderson, 2003). For example, when compared with traditional methods of instruction, the use of simulations as a tool for instigating conceptual change has been studied within mechanics (Gorsky & Finegold, 1992), kinematics (Grayson & McDermott, 1996; Hewson, 1985), electric circuits (Chou, 1998; Lea, Thacker, Kim, & Miller, 1994), optics (Eylon, Ronen, & Ganiel, 1996; Goldberg, 1997), waves (Grayson & Donnelly, 1996), modern physics (Steinberg, Oberem, & McDermott, 1996), as well as across entire physics curricula (Beichner et al., 1999; Van Heuvelen, 1997). The utility of simulations has also been researched as a replacement to physical laboratory work. For example, students who used the PhET simulation *Circuit Construction Kit* (PhET Interactive Simulations, 2019), were shown to build simple circuits faster and displayed better conceptual understanding of circuits as compared to students who were given an analogous physical laboratory setup (Finkelstein, Adams, et al., 2005; Finkelstein, Perkins, Adams, Kohl, &

²⁶ Sometimes referred to as interactive computer-based simulations (ICBS, Zacharia, 2003), interactive simulations (White, 1992), participatory simulations (Wilensky & Stroup, 1999), computer-based manipulatives (Horwitz & Christie, 2000), etc.

Podolefsky, 2005).

However, while it may be sufficient to label the entire category of physics-relevant simulated environments as ‘simulations’ for the majority of work in PER, it is especially pertinent in this thesis for me to further differentiate between various kinds of simulated environments: namely, I make the distinction between *simulations*, *microworlds*, and *games*. In my description of PER-IT, these simulated environments constitute a single topical area which I refer to as *Controllable Worlds*.²⁷

In distinguishing between the types of *Controllable Worlds*, I take the view of simulations as those digital learning environments which allow students to interact with pre-built models of real or hypothesized situations (National Research Council, 2011). Simulations are typically designed around a specific phenomenon or set of phenomena so as to provide students with access to particular disciplinary concepts. In this thesis (esp. in Paper I and II), I investigate the unique learning opportunities afforded by a less phenomenon-specific digital learning environment, *Aldogoo*. In doing so, I make use of the notion of a microworld (Papert, 1980). I use the term to refer to digital environments which offer more opportunities for creativity and invention than what is typically offered by simulation software (Plass & Schwartz, 2014). While simulations tend to allow users to explore the effects of a set of parameters within the given phenomenon, microworlds provide users with the freedom to build their own environments and phenomena, making possible a wider range of scenarios within the same software. As Laurillard (2002) explains, people who use simulations are “controlling a system that someone else has built” while those using microworlds are “building their own runnable system” (p. 162).

In the time since Papert’s (1980) *Mindstorms*, a body of research has amassed examining the function of microworlds. Abelson and diSessa (diSessa, 1980) quickly adopted the LOGO systems in the teaching of advanced mathematics in the Logo Group of the MIT Artificial Intelligence Laboratory and the term ‘microworld’ has persisted in the education research community in the many years since (e.g. diSessa, 1988; Jimoyiannis & Komis, 2001; Mayer, Dow, & Mayer, 2003; Miller, Lehman, & Koedinger, 1999). However, somewhat contrary to Papert’s optimistic view of microworlds, many researchers claim there is a need for some imposed structure of activities or curriculum around a microworld for the environment to become educationally useful (Rieber, 2005; White, 1984). For example, research has shown that, while using LOGO systems, many students do not spontaneously generate the powerful ideas that Papert had intended unless the microworld is used within a context that is “well engineered and targeted at well-defined learning objectives” (Miller et al., 1999; referring to work such as Clements, 1986, 1990; Klahr & Carver, 1988; Lehrer, Randle, & Sancilio, 1989; Pea & Kurland,

²⁷ Here, I borrow ‘controllable worlds’ from Bork (1981), who used the phrase to refer to computer use in physics courses which could “[build] up a student’s insight or intuition” (p. 26).

1984). The topic of microworlds is further discussed in Section 2.4.1.

The third kind of *Controllable World* which exists in PER-IT – and to which my work does not as readily relate – is that of digital games.²⁸ When comparing digital games to simulations and microworlds, Rieber specifies games as *intrinsically motivating* learning environments, especially in terms of their capacity to elicit challenge, curiosity, fantasy, and control (Lepper & Malone, 1987; Malone, 1981; Malone & Lepper, 1987). Another key feature of games may be their tendency to include specific end goals and rewards (Vogel et al., 2006). In some contexts, digital games have been found to have significant promise for improving learning as compared to non-game conditions (D. B. Clark, Tanner-Smith, & Killingsworth, 2016). Nonetheless, digital games have only sparingly been explored within physics contexts by physics education researchers (see, for example, Rose, 2015).

Human-Computer Interfaces: Touchscreens and Haptics

Another topical area of research within PER-IT is that of *Human-Computer Interfaces*. Researchers within this area have tended to investigate how the interactions that humans have with computers are mediated by the physical and virtual design of the technology itself. Devices are now designed to support a wide variety of interactional modalities such as gestures (Pavlovic, Sharma, & Huang, 1997), speech (Potamianos, Neti, Luettin, & Matthews, 2013), haptics (Benali-Khoudja, Hafez, Alexandre, & Kheddar, 2004), eye blinks (Grauman, Betke, Lombardi, Gips, & Bradski, 2003), and more (Jaimes & Sebe, 2007). Researchers within science education have examined how haptic feedback affects students' use of multiple representations (e.g. Schönborn, Bivall, & Tibell, 2011) and how augmented reality setups can encourage conceptual understanding about nanotechnology (e.g. Schönborn, Höst, Palmerius, & Flint, 2014). In this licentiate thesis, I draw on the work done around interactive whiteboard (IWB) use during physics learning.²⁹ On this topic, physics education researchers have explored how interactive whiteboards (IWBs) support students' physical engagement during physics learning (Gregorcic, 2015a, 2015b; Gregorcic, Etkina, & Planinsic, 2015; Gregorcic, Etkina, et al., 2017; Gregorcic, Planinsic, & Etkina, 2017; Mellingsæter & Bungum, 2015). It has been theorized, for example, that large touch screens can allow students to explore phenomena on astronomical time and distance scales by effectively bringing them down to the scale of the human body (Gregorcic & Haglund, 2018). While the interface of the IWB is not the main focus of this thesis, I do reflect meaningfully on the role that the large touchscreen plays in students' physics-relevant interactions.

²⁸ Digital games should not be conflated with the types of 'modeling games' which Hestenes (1992) uses in his modeling approach to physics teaching (see section 2.4.2).

²⁹ Some of the work on IWBs might be, in fact, some of the clearest examples of CSCL research in existing PER (e.g. Gregorcic, 2015b).

Topical areas of PER-IT to which my work does not directly contribute

Microcomputer-Based Laboratory Tools

In a manner exclusive to physics, computer-based laboratory sensors were created to allow students to see graphs of motion simultaneously emerge alongside the movement of a physical object. Research around the use of MBLs has shown improvements in students conceptual understanding of kinematics and graphs (Brasell, 1987; Thornton & Sokoloff, 1990a) as well as dynamics (Thornton & Sokoloff, 1997). Thornton and Sokoloff (1990b) explain how and why they see MBLs as useful tools for physics students, pointing out that the tools allow for student-directed exploration, that data are plotted in real time to allow for immediate feedback, and a wide range of students can use the same set of tools at varying levels. As with most of the technologies discussed in this section, researchers interested in MBL tools often emphasize the importance of quality instruction around the tools in order for the students to benefit (Meltzer & Thornton, 2012; Thornton, 2008). Examples of curricula which involve MBL use are *Workshop Physics* (Laws, 1991; Laws et al., 2015) and *RealTime Physics* (Sokoloff et al., 2007; Thornton & Sokoloff, 1997). Other more recent efforts have shown how MBLs such as the iOLab (www.iolab.science) or infrared cameras can be studied in small group work with social semiotics (e.g. Samuelsson, Elmgren, & Haglund, 2019; Volkwyn, Airey, Gregorcic, Heijdensköld, & Linder, 2018). Trumper (2003) offers a further review of MBLs in the context of the physics laboratory.

Programming

Starting in the era of pre-PER curricula development projects, Alfred Bork was an early proponent of programming in the physics classroom. For example, he devised an introductory college physics course around *The Feynman Lectures on Physics* (Feynman, Leighton, & Sands, 1964), which called for students to use the computer to numerically solve some of the problems posed by Feynman (Bork, 1964). As computing power increased rapidly in the 1970s and 1980s, research efforts such as the Maryland-based MUPPET project began incorporating higher-level programming into the physics classroom. These efforts were later used as part of the Comprehensive Unified Physics Learning Environment (CUPLE) project (Redish, Wilson, & McDaniel, 1992) and the CUPLE physics studio (J. M. Wilson, 1994). *Programming* research efforts have tended to be used to expand the physics curricula, to involve students in the authentic practices of modern physicists, or to expose students to the inherent systematic structure of the programming language.³⁰ For a discussion of the involvement of programming in physics teaching and learning, see the American Association of Physics Teacher's policy document on the issue (AAPT Undergraduate Curriculum Task Force, 2016).

³⁰ In this latter sense, programming in physics instruction tends to look more like Papert's microworld vision with the Logo programming language (see section 2.4.1).

Student Response Systems (Clickers)

Student response systems (SRSs), are a family of handheld digital devices which can be used by students to wirelessly respond to teacher prompts, especially in lecture-based settings. These ‘clicker’ systems were first developed by the US military in the 1950s (Abrahamson, 2006) and eventually came into use by both Stanford University and Cornell University by the late 1960s (Aljaloud, Gromik, Billingsley, Wing, & Kwan, 2015). SRS use is particularly common in science classrooms,³¹ where in some cases, entire physics departments commit to using SRSs in their large lecture courses (Keller et al., 2007). Student-centered physics curricula such as *Peer Instruction*³² (Mazur, 1997) or *Just-in-Time Teaching* (Novak et al., 1999) are particularly good matches for SRSs due to their emphasis on students receiving consistent feedback during lecture. PER scholars have found that SRSs are viewed by physics students to be predominantly useful, especially when the technology is implemented alongside frequent peer discussions and conceptual questions (Keller et al., 2007). Other PER work suggests that SRSs are useful to varying degrees for different students and different topics (Sayer, Marshman, & Singh, 2016). For a more in-depth (albeit not physics-specific) discussion of SRS technology, see Aljaloud et al. (2015).

Tutors and video

Much of the early work in PER-IT was aimed at designing and implementing artificially intelligent tutor systems. Recent versions of these computer dialogs exist with “sophisticated hints, guidance, and feedback” (Docktor & Mestre, 2014, p. 12) and in some cases have become mainstays of introductory physics course homework (Kashy et al., 1993, 1995; Kortemeyer et al., 2008; Lee et al., 2008; Pascarella, 2002) or tutorials (Reif & Scott, 1999). Research in this area has reported mixed results, with studies comparing web-based homework to traditional pencil-and-paper homework showing either no difference (Bonham et al., 2003) or improved performance (Cheng et al., 2004; Mestre, Hart, Rath, & Dufresne, 2002; Morote & Pritchard, 2009; VanLehn et al., 2005). Within this topical area, I include the work of Dean Zollman and others to incorporate interactive videos into the physics teaching (e.g. U. Eriksson, Linder, Airey, & Redfors, 2014; Zollman & Fuller, 1994), since videos were a relatively common addition to CAI methods. Nonetheless, a case could certainly be made that that the PER work on interactive video deserves a topical area to its own,

³¹ The iClicker system, currently self-reported as the ‘market leader’ in SRS technology (www.iclicker.com), was originally developed by a team of physics educators at the University of Illinois Physics Department in 1997 (including Tim Stelzer, Mats Selen, Gary Gladding, and Benny Brown) (MacMillan Learning, 2019).

³² Despite the oft-pairing of SRS technology with *Peer Instruction*, Mazur makes it clear that the teaching approach is not reliant on any particular technology. For example, he suggests that flashcards could be used just as effectively as clickers when implementing *Peer Instruction* (see Lasry, 2008 for a discussion of this topic).

as in many ways this work helped usher multimedia instructional tools into the physics community (Wittmann, 2005).

Distance learning (e-learning)

With the advent of the Internet, the computer became a viable tool for bridging physical gaps between teachers and students. As a result, digitally-enabled distance learning has emerged as an educational approach with hopes of democratizing access to learning, minimizing costs, and reaching larger audiences than in-person instructional methods. Within PER, investigations around distance learning have tended to examine student demographics and enrollment rates. For example, researchers have found that Massive Open Online Courses (MOOCs) can lead to much higher attrition rates than traditional, ‘brick-and-mortar’ courses, which some researchers take to suggest that successful MOOCs students may need higher levels of self-motivation (e.g. Dubson et al., 2014; Lieberman, Dubson, Johnsen, Olsen, & Finkelstein, 2015). Other physics education researchers have examined students peer discussion online (Duda, Garrett, Henderson, Sabella, & Hsu, 2008; Kelley, Gavrin, & Lindell, 2018) or examined the results of concept tests in distance learning environments (Aiken et al., 2014; Chudzicki, Chen, Zhou, Alexandron, & Pritchard, 2015).

2.2.3 My position in PER-IT

From a historical perspective of PER-IT, I position this thesis within the CSCL paradigm. That is, I concern myself with how students’ interpersonal interactions are shaped by the presence of dynamic software. As discussed in Section 2.2.1, CSCL has thus far gained little traction within PER, so I see my efforts to study CSCL within physics contexts as a foray into a relatively underexplored area for the PER community. PER work within CSCL is worthwhile – especially when viewed from a DBER-allied perspective – insofar as there are insights to be gained about how students collaborate around technology which are particular to physics teaching and learning. Conversely, since scholars of the CSCL tradition outside of PER may find value in the examination of new contexts, the work of this thesis could be of value for the broader community of researchers interested in CSCL.

In relating my work to the existing work in PER-IT, I see this thesis contributing to the topical areas of *Controllable Worlds* and *Human Computer Interfaces*. In Papers I and II, I concern myself with how students make use of an open-ended, microworld-like software, *Algodoo*. In Paper III, I study students’ interactions around the *My Solar System* simulation software from PhET. In this way, I utilize theoretical perspectives apt for the area of *Controllable Worlds*. Across all three of these papers, I have examined how small groups of students use these software on an interactive whiteboard (IWB). While I do not explicitly examine the affordances of the IWB for use in physics teaching and learning, in this thesis I discuss how the enlarged size and

interactivity of the IWB has seemed to be consequential for students' interactions during physics-relevant collaboration.

Especially through my focus on students' moment-to-moment communication – and through my involvement of theoretical perspectives such as embodied cognition, conceptual metaphor, social semiotics, and conversation analysis – I also see my licentiate work relating to research on (what I refer to as) Language and Social Interaction (LSI). Among the many other influences of technology discussed above, “digital technologies [have] enable[d] image, sound and movement to enter the communicational landscape in new and significant ways” (Jewitt, 2017, p. 19). In the next section, I will briefly review the relevant trends of LSI (esp. within PER) and position myself in terms of the existing research efforts of this third and final field.

2.3 Language and social interaction in PER

In this section, I will review the PER work done in the area language and social interaction (which I abbreviate as PER-LSI). To do so, I will first review how the field of research on LSI developed within the 20th century, in particular, highlighting how the traditions of linguistics and interactionist sociology/anthropology have both come to value *embodied* forms of meaning making alongside talk and written text. Then, as I have already done with the sections on PER and PER-IT, I will review the relevant topical areas of PER-LSI and position my licentiate thesis in relation to the existing efforts on this topic.

2.3.1 The ‘embodied turn’ in LSI research

To begin, I first review the historical development of LSI research. In his review of the field of LSI, Maurice Nevile (2015) discusses what he calls *the embodied turn* of LSI research: that is, “the point when interest in the body became established among researchers on language and social interaction” (p. 121). Nevile examines articles published in the journal *Research on Language and Social Interaction* from 1987 to 2013 and notes that – especially within the tradition of conversation analysis – there was a relative surge in papers taking an explicit focus on embodiment from the year 2001 and onward. This focal shift of LSI research from talk/language to talk-plus-embodiment was at least in part due to the increasing ease of collecting video data, but also drew on the foundational work of a number of researchers from the 1960s, 1970s, and 1980s. In this section, I will review how these earlier LSI researchers – with diverse backgrounds in linguistics and sociology/anthropology – first came to value embodiment's role in communication.

Embodiment in the linguistic tradition of LSI

Neither linguists nor psychologists have begun the study of conversation; but it is here we shall find the key to a better understanding of what language really is and how it works.

(Firth, 1935, p. 71)

In the 19th century, scholars of *semiotics* such as Charles Peirce (as a philosopher and logician) and Ferdinand de Saussure (as a linguist) studied the nature of signs, the things those signs signified, and the individuals who interpreted those signs.³³ Their bodies of work would form the foundation for much of the modern research on language and its role in social interaction. By the 1920s – amidst a ‘linguistic turn’ of intellectuals in the early 20th century (Hacker, 2007) – the Soviet linguist Valentin Vološinov had developed a Marxist-inspired theory in response to Saussure which aimed at contextualizing semiotics within social processes (Vološinov, 1930). For Vološinov, any meaningful study of language could not ignore the social context within which language occurred. Another scholar, the English linguist J. R. Firth, viewed linguistics as a means of understanding the relationship between individuals and society. Building on the work of Firth, linguist Michael Halliday (1975) described “language as a form of social semiotic” (p. 170). Halliday sought to explore the ‘functional grammar’ of language:

Language has evolved to satisfy human needs; and the way it is organized is functional with respect to those needs – it is not arbitrary. A functional grammar is essentially a ‘natural grammar’, in the sense that it can be explained, ultimately, by reference to how language is used.

(Halliday, 1994, p. viii)

Through these efforts, Halliday established systemic functional theory (SFT), which posited the necessary criteria (in the form of three ‘metafunctions’) that language had to meet in order to act as a resource for making meaning. More importantly for this thesis, it is worth noting that Halliday recognized other (semiotic) systems than language which people use to make meaning, such as paintings, sculptures, music, dance, modes of dress, etc. (Halliday & Hasan, 1985).

In the 1980s, an influential group of scholars, namely the *Newtown Semiotic Circle* from Sydney, began building on Halliday’s work by examining the different modes of communication which were present in ‘integrated’ texts.³⁴

³³ Saussure technically worked in a subset of semiotics, which he referred to as *semiology*, and tended to focus on the sign and signifier in an abstract sense (intentionally excluding the role of the interpreter).

³⁴ Though linguistic research continued to focus on written and visual texts through the 1990s, a ‘text’ is now commonly treated as any semiotic object of study. For example, a text could be a painting, film, or conversation.

The list of researchers included Gunther Kress, Robert Hodge, Theo van Leeuwen, Jim Martin, Paul Thibault, and Terry Threadgold and, through their collaborations, these researchers would go on to found the field of *social semiotics* (Jewitt, Bezemer, & O'Halloran, 2016). Examples of early social semiotics research include studies of children's drawings and pages from textbooks (Kress & Van Leeuwen, 1990). Jay Lemke, who pragmatically incorporated notions of social semiotics into his work on representations in science, published well-known *Talking Science* around the same time (Lemke, 1990). Through the 1990s, then, research within social semiotics (and more broadly, linguistics) expanded its focus from only written and spoken language to images alongside text.

However, it was not until the 2000s that social semiotics was meaningfully applied to the study of social interactions between individuals. For example, Kress et al. (2001) studied interactions in the pre-college science classroom and later in the teaching of English (Kress et al., 2005). It was during this time that embodiment began to feature prominently in social semioticians' lexicon. As the range of studied meaning-making systems expanded, researchers also began embracing the label of *multimodality* (Kress, 2010). For the purposes of this thesis, multimodality can be thought of as the notion that humans communicate in a variety of ways (Jewitt et al., 2016), that is, not only with written and spoken language but also with gestures, gaze, manipulation of objects, static and dynamic images, haptic-touch,³⁵ body posture, etc. Thus, in a way similar to how the social semiotics of the 1980s and 1990s had incorporated images into the linguists' field of concern, the studies of interaction and multimodality in the 2000s encouraged linguists to appreciate embodiment (among other things) in their research.

Embodiment in the sociological/anthropological tradition of LSI

In the 1960s, researchers from a background in sociology/anthropology had already taken up the study of interactions as a means of better understanding individuals' lived experience. In particular, Harvey Sacks and Emanuel Schegloff, researchers at the University of California, Berkeley, helped establish a "distinct theoretical and methodological approach to the study of social interaction" (Jewitt et al., 2016, p. 86), which we now call *conversation analysis*. These early conversation analysis researchers studied social action by examining the ways in which individuals navigated from one moment to the next during conversation. For example, Schegloff and Sacks (1973) studied recordings conversations as a means for demonstrating the prevalence of 'adjacency pairs' in conversational turn-taking.

By the 1970s, scholars such as Charles Goodwin began use *video*

³⁵ By haptic-touch, I mean to refer to interpersonal contact which might act to push or pull an individual (i.e. human-human contact that includes a force, rather than, for example, the feeling of a surface's texture) (see section 2.4.3).

recordings as the data for conversation analysis. The use of video data enabled researchers to examine the role that non-verbal language played in conversations. For example, Goodwin (1979) famously examined how the single phrase, 'I gave up smoking cigarettes one week ago today actually,' was augmented by a speaker's gaze during a dinner conversation. It was during this time that sociologists/anthropologists began appreciating embodied actions as necessarily included alongside spoken language during studies of interaction. From the 1990s onward, Goodwin began analyzing interactions which were placed within increasingly diverse contexts (i.e. at an archaeological dig site or in the chemistry classroom). As he did so, he came to discuss how conversing individuals made use of their surroundings and their bodies in a mutually-elaborating, environmentally-coupled manner (Goodwin, 1994, 2000, 2007). Central to conversation analysis was the notion that meaning was built-up from a range of semiotic systems:

Saussure [...] called for a science focused on the general study of signs. However, like most work in Semiotics that followed, he then defined his task as the study of a single semiotic system, in his case language. The study of how individual semiotic systems are organised has made enormous contributions to our understanding of the cognitive and social organisation of humans and of other animals. However, [...] it is also necessary to investigate how different sign systems work together to build relevant action and accomplish consequential meaning. By virtue of this potential synergy (indeed symbiotic relationships between systems of signs) any single system need provide only a partial specification of what is necessary to accomplish relevant meaning and action.

(Goodwin, 2003, p. 36)

As was the case with linguistics, it is around this time that the label *multimodality* was applied to conversation analysis. However, as Jewitt et al. (2016) note, the community of researchers who tend to use conversation analysis have not integrated the badge of 'multimodality' into their subfield to the degree that social semiotics (or SFT) has. In this licentiate thesis, I take the stance of using multimodality in combination with both social semiotics and conversation analysis. Thus, I find it useful to occasionally use the terms 'multimodal social semiotics' and 'multimodal conversation analysis.'

As Nevile (2015) describes, the 2000s saw an 'embodied turn' in LSI research: both linguists – through their increasingly multimodal efforts in SFT and social semiotics – and also sociologists/anthropologists – through their increasingly multimodal efforts in conversation analysis – began foregrounding the body and embodied actions alongside the spoken and written language. Of particular note here is how recent this attention to embodiment has been fostered within the community of LSI researchers. As I discuss below, the relative newness of embodiment in LSI has meant that embodied communicational resources, especially as a focus of analytic attention, have consequently been applied to the field of PER only sparingly thus far.

Beyond the fields of linguistics and sociology/anthropology, there was a similar turn toward embodiment in cognitive psychology in the 1970s and 1980s. For example, George Lakoff and Mark Johnson developed their seminal theory of conceptual metaphor by 1980 (Lakoff & Johnson, 1980) and this has since led to the psychological theories of embodied cognition and situated cognition. For a further discuss of these cognitive approaches (of which this thesis makes use), see Section 2.4.4.

2.3.2 The existing PER-LSI work and my position in it

As mentioned in Section 2.1.2, there exists a collection of physics education researchers who have examined topics related to LSI. The relevant literature here includes research on how students make use of multiple representations (e.g. Van Heuvelen, 1991b; Van Heuvelen & Zou, 2001) as well as research on the effect of subtle changes to the names of physics topics such as heat in improving students' conceptual understanding (e.g. Brookes & Etkina, 2015). Other researchers have focused on the role of analogies in structuring student reasoning (e.g. Clement, 1993; Duit, 1991; Haglund & Jeppsson, 2012; Niebert, Marsch, & Treagust, 2012), often framed by the conceptual metaphor work by Lakoff and Johnson (1980). Some of these researchers have utilized Halliday's SFT to study the functional grammar of physics learning (Brookes & Etkina, 2007, 2009). A common feature of most of this work is examination of students' reasoning via their written or spoken language. Even with the rising frequency of qualitative work within PER which takes student interviews as data, it has been relatively uncommon for physics education researchers to examine the range of semiotic systems which students use to communicate and make meaning (notable exceptions include Gregorcic, Planinsic, et al., 2017; Harrer, 2018; Scherr, 2008; Scherr, Close, Close, & Vokos, 2012; Scherr, Close, McKagan, & Vokos, 2012).

This is the first way in which I position this thesis in terms of PER-LSI: my work takes the approach of analyzing students' *multimodal* interaction on a moment-to-moment basis, and to do so, makes use of the conversation analysis approach put forward by Goodwin and others. In doing so, I see my research in this thesis as an embracing the 'embodied turn' which has occurred in LSI within the past two decades. Russ and Odden (2018) state the research which "[pushes] our understanding of the modalities we can analyze in video records of student learning" represents a frontier along which future qualitative work in PER can expand. This thesis, in part, represents an exploration along this methodological frontier.

Parallel to the work done in representations and language, a number of physics education researchers have recently incorporated social semiotics into their examination of physics teaching and learning (e.g. Airey & Linder, 2017; Tobias Fredlund, 2015; Tobias Fredlund, Airey, & Linder, 2012; Tobias Fredlund et al., 2015a; Samuelsson et al., 2019; Volkwyn, Airey, Gregorcic,

& Heijlenskjöld, 2019; Volkwyn et al., 2018). As Airey and Linder (2017) discuss, these social-semiotic efforts in PER differ from other ‘representations’ approaches in PER in three key ways. First, physics education researchers applying social semiotics tend to start with “the ways in which professional physicists make and share meaning using semiotic resources” (p. 98). That is, these researchers look how the social *group* of physicists communicates meaning in the form of disciplinary semiotic resources and, in turn, how *groups* of teachers and students make use of those resources. Second, the social-semiotic approaches to PER tends to include a focus on a range semiotic resources (e.g. laboratory apparatus and physical actions) which other ‘representations’ efforts have traditionally ignored.³⁶ Finally, physics education researchers using social semiotics have tended to view the range of *meaning potentials* that semiotic resources carry. That is, these researchers appreciate the multiplicity of meanings that can be derived from disciplinary-specific semiotic resources, highlighting how students must discern what aspects of a disciplinary resource are relevant within a particular context.

This leads to the second way that I position my thesis within existing PER-LSI: that is, in relation to the application of social semiotics to physics teaching and learning. In addition to the conversation analysis approach I take in collecting and analyzing students’ interactions, I also incorporate the social-semiotic practices of focus on the group, attention to a range of semiotic resources, and an examination of the potential meanings associated with semiotic resources. However, while social semiotics often takes the semiotic resources of the *discipline* as the starting point, in this thesis I choose to start with an attention to the semiotic resources generated and utilized by the students. In this way, I see my work as contributing a student-centeredness to the developing tradition of social semiotics in PER. For a further discussion of the perspective of social semiotics and my relationship to it, see Section 2.4.3.

2.4 The perspectives taken in this thesis

During my discussion of my relative positions within the fields of PER, IT, and LSI, I have mentioned a range of theoretical perspectives which I take in this licentiate thesis. However, I have so far refrained from explaining these theoretical underpinnings at depth for the sake of brevity while positioning my work. I now review each of the theoretical perspectives taken in this thesis to further explain the underpinnings of my research. While doing so, I will also introduce some relevant terminology which I use throughout the remainder of this thesis.

³⁶ This has come to include the ‘embodied’ resources discussed above to a lesser degree, since those resources which are typically seen as disciplinary are infrequently expressed with the human body.

2.4.1 Constructionism and microworlds ^{II}

In his controversial book, *Mindstorms*, Papert (1980) presented a family of computer-based tasks (“Logo systems”) which involved small programmable robots alongside Logo-capable computers. Papert argued that Logo systems could provide students with a sufficiently enticing environment for them to develop, in a relatively intuitive and spontaneous way, a mathematical language to communicate with computers. Just as a learner of French might immerse themselves in the French language by visiting France, he suggested a learner of mathematics could immerse themselves in the “Mathland” (p. 6) cultivated within the Logo systems.

Papert intended to provide students with an arena where they could explore formal topics in informal ways. By introducing what he characterized as *microworlds*, Papert aimed to make computer programming and even the formalisms of Newtonian mechanics accessible to students. In contrast to what he considered the often ineffective and ingenuine approaches taken by much of traditional education, Papert believed that the use of microworlds would result in “Piagetian learning,” or informal “learning without being taught” (p. 7). He believed that this could be done by providing arenas which were rich in the building blocks needed for students to explore, create, and experience formal concepts for themselves. In order to motivate and facilitate the students’ learning process, Papert argued that microworlds needed to allow students to become active *builders* in the environment and support them in taking the initiative to engage creatively with the provided materials. The role of a microworld was thus twofold: it needed to (1) offer the correct *materials* for students to recruit and (2) provide a *space* where students could be inspired to create with these materials.

In arguing for builder-focused microworlds, Papert developed what is referred to as a *constructionist* perspective on learning. This constructionist approach places explicit emphasis on the students’ act of building – or *constructing* – as a means of learning.

Constructionism – the N word as opposed to the V word – shares constructivism’s connotation of learning as “building knowledge structures” irrespective of the circumstances of the learning. It then adds the idea that this happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it’s a sand castle on the beach or a theory of the universe.

(Papert, 1991, p. 1)

In this way, the constructionist perspective can be seen as a special case of the broader, more commonly known approach of constructivism. A good example of constructionism-influenced teaching approaches is that of problem-based learning. Students in such settings are encouraged to actively produce (construct) objects in the physical/digital world so as to involve their bodies in the process of learning through discovery.

It is important to note that the definition of a microworld, and how the concept of microworlds compares to simulations or games (see Section 2.2.2), is not without contention in the literature. Rieber (1996) discusses the classification of microworlds, suggesting that a learning environment can be regarded as a microworld if it acts as such for a particular learner:

In a sense, then, it is the learner who determines whether a learning environment should be considered a microworld since successful microworlds rely and build on an individual's own natural tendencies toward learning. It is possible for a learning environment to be a microworld for one person but not for another.

(Rieber, 1996, p. 46)

For Rieber, a learning environment should, therefore, be considered as a microworld in its specific use within a particular context. It is precisely this user-subjective perspective on microworlds that I use in Paper II of this thesis: whether or not a software can be unanimously identified as a microworld for all students, I concern myself with how the software *acts* as a microworld for certain students as they use it, particularly when dealing with mathematical concepts in a physics context.

2.4.2 Semi-formalisms and modeling ¹

In the early years of research into digitally-assisted learning in physics, diSessa (1988) described a unique role for creativity-driven digital environments such as microworlds. He hypothesized how computers might provide students access to *semi-formalisms*, which he described as access points to the formal ideas of physics in ways that could be strongly related to their everyday experiences. In this thesis, I make use of diSessa's term, *semi-formalism*, to show how open-ended software (like *Algodo*) can play a mediating role between the physical world and the mathematical formalisms used in physics. To do so, I examine how *Algodo* was used in student's mathematization by functioning as a semi-formal means for modeling (Paper I).

Many education researchers see modeling (in the broad sense) to be the fundamental enterprise of physics. Notably, Hestenes (1992) claims that physics teachers should explicitly provide students with the rules by which the physics modeling "game" is played out as a scientific activity. For him, this entails that physics teachers should create learning environments that show

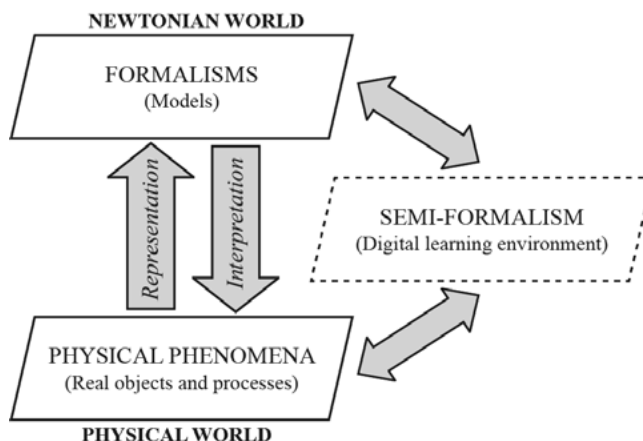


Figure 3. Hestenes' (1992) "Newtonian Epistemology" (left) modified to include a digital semi-formalism (right, shown with a dashed border), which mediates between the physical world and the Newtonian world (of formalisms).

students how modeling underpins the constitution of physics knowledge. In this way, Hestenes claims that enabling students to build, inspect, and use models is at the core of quality physics teaching.

In Paper I, I have combined the theoretical ideas of diSessa and Hestenes for the examination of students' use of *Algodo*. Figure 3 shows a modified version of Hestenes' visualization for the relationship between the physical world (bottom) and the collection of models used within the Newtonian tradition (top). In this modified version, I have included my interpretation of where a semi-formalism would reside in this system (right). DiSessa suggested that semi-formalisms would provide alternative means for accessing the formal, mathematically rigorous ideas used in physics (in a manner which is more similar to their experiences of the physical world) which I show as vertical halfway point between Hestenes' (1992) two worlds.

2.4.3 Multimodal social semiotics ^{III}

As discussed in Section 2.3, though language in written and spoken forms has historically monopolized the attention of those researchers and philosophers concerned with communication, a growing number of scholars in education (both generally and within PER) are beginning to attend to an expanded picture of communication (Airey & Linder, 2017; Fredlund, 2015; Fredlund, Linder, et al., 2015a; Gregorcic, Planinsic, et al., 2017; Harrer, 2018; Scherr, 2004; Volkwyn et al., 2018). These researchers are doing so by considering the multiplicity of ways by which individuals communicate beyond written and spoken language, that is, through a lens of multimodality (Jewitt et al., 2016; Kress, 2010). While multimodality is a perspective applied across many disciplines and to a variety of research topics, one school of multimodal

thought that has been meaningfully adapted into the domain of PER is that of social semiotics (Airey & Linder, 2017; Weliweriya, Sayre, & Zollman, 2019).

Social semiotics is the study of how social groups of people – from the scale of paired conversations up to the scale of societal contexts – develop and reproduce “specialized systems of meaning making,” as realized through *semiotic resources* (meaning-making resources) (Airey & Linder, 2017, p. 95). Within PER, studies utilizing social semiotics tend to take as a starting point the *meaning potential* of semiotic resources (these are the items often referred to as representations) used in the discipline of physics. An important area of interest for such researchers is the ways in which students develop “fluency” in the use of disciplinary semiotic resources and gain the ability to strategically select and coordinate resources by recognizing a set of disciplinary-relevant aspects (DRAs)³⁷ relating to the task at hand (Airey, 2009; Airey & Linder, 2009, 2017; U. Eriksson, 2014; Fredlund, Airey, & Linder, 2015; Fredlund, Linder, & Airey, 2015b; Fredlund, Linder, et al., 2015a). Among other things, studies using this framework have found that semiotic resources which stand fast – or are persistent (e.g. graphs, diagrams, sketches) – play a central role in meaning-making by serving as a hub around which other non-persistent resources (i.e. talk and gesture) can be coordinated (Fredlund et al., 2012; Volkwyn et al., 2019, 2018).

As discusses in Section 2.3.2, I depart from the typical implementations of social semiotics in PER. I examine how students employ *non-disciplinary* resources while addressing DRAs of physics phenomena. To do so, I utilize and incorporate the analytic techniques from conversation analysis, taking students’ moment-to-moment interactions as my focus. Whereas social semiotics tends to take as its analytical starting point the resources of the discipline (though not exclusively so, e.g. Volkwyn et al., 2018), *conversation analysis* (discussed below) tends to start analytically with the resources used by individuals as they engage in conversation.

2.4.4 Multimodal conversation analysis ^{III}

Conversation analysis involves the micro-level (moment-to-moment) examination of video-recorded conversations in order to determine how individuals build up actions and interactions in multimodal sets of mutually-elaborating semiotic resources (Jewitt et al., 2016; Streeck, Goodwin, & LeBaron, 2011). For example, Goodwin (2003, 2007) used conversation analysis to examine how archeologists use gestures closely linked to their setting – which he calls environmentally-coupled (or symbiotic) gestures – alongside talk to communicate within a dig site. In conversation analysis, systems of semiotic resources like gesture, gaze, and body positioning are considered in concert with

³⁷ Disciplinary-relevant aspects (DRAs) are “those aspects of physics concepts that have particular relevance for carrying out a specific task”(Fredlund, Airey, et al., 2015, p. 2).

the spoken and written words which occur simultaneously or in sequence. For Goodwin and other conversation analysts, multimodal utterances – i.e. those ‘chunks’ of externalized communication which might include any range of semiotic resources – should be analyzed not only as expressions made by communicating individuals but also as social acts which function to produce meaning with other sets of individuals. It is precisely this notion of building up action from a multimodal set of semiotic resources, along with the methodological practices of close analysis and transcription of video footage, that I find useful for this thesis.

Paper III deals with the analysis of an interpersonal ‘dance.’ Thus, I will pay attention to the (relatively uncommon) semiotic resource system of haptic-touch. Literature on haptic-touch, or simply haptics, can be found predominantly in the domains of human-computer interface research – where the tools used to interact with computers have begun to incorporate resistive feedback or other sensorimotor stimuli (Jones, Minogue, Tretter, Negishi, & Taylor, 2006) – and cognitive psychology research (e.g. Gallace & Spence, 2010). Within social semiotics, (haptic-)touch has received minimal attention. Much of the discussion has centered on whether touch should qualify as a semiotic resource system in its own right – specifically, whether touch meets three necessary criteria (“metafunctions”) for constituting a communicational mode in the same way that talk or gesture do (Bezemer & Kress, 2014; Crescenzi, Jewitt, & Price, 2014; Flewitt, Kucirkova, & Messer, 2014; Jewitt et al., 2016). For the purposes of this thesis, I accept haptic-touch as a semiotic resource system insofar as I see it being used by students while make meaning with one another.

2.4.5 Embodied cognition and conceptual metaphor ^{III}

The body has been viewed by many cognitive psychology scholars as an integral and noteworthy counterpart to the mind since the 1980s, specifically in the branch of cognitive science which is termed *embodied cognition* (see review in Amin, Jeppsson, & Haglund, 2015; Roth & Lawless, 2002b; M. Wilson, 2002). Originally arising as a response to the isolationist versions of cognitive science that viewed the mind as a discrete information processor, embodied cognition is characterized by a focus on how personal bodily experiences, which are often common across individuals due to the similarity of our human bodies, serve to structure cognition and language. One of the more influential traditions of embodied cognition research, Lakoff and Johnson’s (1980) *conceptual metaphor*, centers around how humans form basic units of intuition called *image schemas* and recruit these schemas metaphorically during cognition and communication. From the perspective of embodied cognition/conceptual metaphor, then, image schemas are seen as the (pre-linguistic) building blocks from which cognition is built and which individuals acquire through repeated sensorimotor experiences.

The perspectives of embodied cognition and conceptual metaphor have been fruitfully applied to science education research, particularly in studies which focus on students' use of analogy and metaphor in their spoken and written language (Amin et al., 2015; Jeppsson, Haglund, & Amin, 2015; Niebert & Gropengiesser, 2015; Niebert et al., 2012; Roth & Lawless, 2002a). As discussed in Section 2.1.2, PER has seen the emergence of theories similar to conceptual metaphor with the Knowledge in Pieces models of cognition (diSessa, 1988, 1993; Hammer, 1996a; Redish, 2004). Another related framework is that of conceptual blending, which builds on the work of Fauconnier and Turner (1998) and which has recently received attention among a collection of physics education researchers (e.g. Close & Scherr, 2015; Dreyfus, Gupta, & Redish, 2015; Gregorcic & Haglund, 2018; Hoehn & Finkelstein, 2018).

However, while these irreducible, infinitesimal cognitive units of image schemas (or p-prims and resources) are useful constructs for discussing how the experiences of the body get into our thoughts and language, for the purposes of this thesis, I take a perspective which accounts for a larger grain size of cognitive unit. As I discuss in Chapter 5, a main impetus for Paper III was to meaningfully analyze the semiotic function of an enacted dance carried out by a pair of students. As such, I posit that an atomization of a complex act such as dance into irreducible image schema or p-prims would categorically miss one of the main affordances of the dance for the students: the dance evoked a single coherent mental image rather than an impromptu cobbling-together of basic cognitive units. The dance appears to have functioned as a prefabricated, mutually understood act for the students.

Therefore, in Paper III I choose to interpret students' cognition – during the dance and otherwise – in terms of larger 'chunks' of mental imagery (Clement, 2008; Reiner & Gilbert, 2000). I refer to these 'meso-scale' cognitive units – which I emphasize are neither the 'microscopic,' irreducible building blocks nor 'macroscopic' conceptions – as *embodied imagery*. By embodied imagery I mean to denote the source domain of the students' metaphoric language which is grounded (Barsalou, 2008) in embodied experiences with the material world. In doing so, I see myself aligning with Reiner and Gilbert (2000) in the view that “students construct meaning on the basis of mental structures of embodied imagination of a figurative, dynamic, non-propositional character” (p. 502). To a degree, my perspective also resembles the 'resource framework'³⁸ (Hammer, 2000; Redish, 2003, 2004). Within the resource framework, an individual's long-term memory is seen as built up from both smaller 'reasoning primitives' (akin to image schemas and/or p-prims)

³⁸ The “resources” of this cognitive framework should not be conflated with the “semiotic resources” from the social semiotic framework discussed in Section 2.4.3 and before. While I use a cognitive model which does bear some resemblance to the framework with the former use of the term, my analysis in this paper makes use of the term ‘resources’ in accordance with the latter.

and also larger units called ‘facets’ (i.e. reasoning primitives which have been mapped/applied to phenomena or objects in the concrete world). Though the relative size of facets as compared to primitives is not expressly discussed in the literature, I see a resemblance between the resource framework’s *facets* and my *embodied imagery* in that they both contain a grounding in concrete experiences that appear to be called upon as a larger ‘chunks’ of cognition (as opposed to irreducible cognitive units). Still, by highlighting both the embodied nature of students’ cognitive structures as well as the metaphorical nature by which they come to be used in the students’ multimodal interaction, I suggest that an analysis which is aligned most closely to the framing of the embodied cognition/conceptual metaphor perspective offers something new and worthwhile to the PER community.³⁹

2.4.6 Kinesthetic/embodied learning activities ^{III}

The realization that learning is not only cognitive, but can also involve the body of the learner, has long captured the attention of philosophers, educators, and education researchers (Dewey, 1916; Merleau-Ponty, 1945). In the domain of physics education, interest in embodied learning has likely stemmed from the fact that much of physics’ subject matter deals with the actions and interactions of objects at the scale of the human body (Redish, 2014). Thus, involving students’ bodies as active instruments and sensors can be a natural and intuitive approach for the interested physics educator: for example, students can feel forces (pressure) as they sit on carts and push each other around (Bracikowski, Bowman, Brown, & Madara, 1998); or, they can push objects along surfaces with varying coefficients of friction to ‘feel’ the resistances those surfaces provide (Besson, Borghi, De Ambrosis, & Mascheretti, 2007). Even beyond phenomena at the human scale, there are educational advantages to be found in encouraging students to act as metaphorical role-players in processes physically much smaller (Mcsharry & Jones, 2000) or much larger than themselves (McDermott et al., 1996b): such embodied learning allows students to relate their bodily intuitions to objects in otherwise physically-nonintuitive domains.

Nonetheless, much of the existing PER work on bodily engagement in physics learning has not gone much beyond tracking the design and implementation of explicit instructional activities wherein students’ bodies are included at the request of teachers. Here, the topic of the body as a tool for learning is often mentioned under the label of kinesthetic learning or kinesthetic learning activities (KLAs). Begel et al. define a KLA as an “activity which physically engages students in the learning process” (2004, p. 1). By

³⁹ A similar analysis to the one carried out in Paper III could perhaps be carried out with a commitment to a ‘p-prims’ or ‘resources’ approach. Still, I do not expect the insight generated from such an approach to be equivalent to what I present in Chapters 5 and 6 from Paper III.

this definition, KLAs include activities such as laboratory work or demos where students might interact with physical apparatus (e.g. Trout & Gaston, 2001) but also those activities where students might use their bodies as sensors for physical interactions (e.g. Bernhard & Bernhard, 1999; Bruun & Christiansen, 2016; Coletta et al., 2019; de Oliveira & Fischer, 2017; Richards, 2019; Richards & Etkina, 2013; Ruiz, 2017; Sliško & Planinšič, 2010; Whitworth et al., 2014). Perhaps unsurprisingly, KLAs are quite common in the physics literature as a way of leveraging students' bodily experience to make sense of physics phenomena. KLAs have been shown as potentially effective means for engaging students (Sivilotti & Pike, 2007) and improving learning outcomes in particular settings (Begel et al., 2004).

While the label of KLAs seems to apply to a broad range of activities which involve the body, finer distinctions and reformulations have been made to distinguish certain activities involving the body from others. Scherr et al. (2012) introduce the concept of embodied learning activities (ELAs) as a subset of KLAs. In ELAs, a teacher incorporates students' bodies, or parts of their bodies, as metaphorical substitutes for physical entities in a role-playing of physical phenomena (e.g. Manogue et al., 2001; McDermott et al., 1996b; Mcsharry & Jones, 2000; Morrow, 2000; V. Singh, 2010). This is in contrast to the more generic KLAs, where a teacher incorporates students' bodies as sensors and non-metaphorical participants in phenomena. For example, in Scherr et al.'s (2012) prototypical example of an ELA, *Energy Theater*, students represent physical manifestations of energy, moving between designated locations in a room to enact transformations of energy such as in chemical bonding or in the heating of a lightbulb. Alternatively, a KLA on the same topic might involve the students using their hands to feel endothermic reactions or touch the surface of a light bulb in a circuit (Haglund, Jeppsson, & Schönborn, 2016). By involving the students' bodies as representations of physical entities, ELAs can help students draw and explore metaphorical parallels between characteristics of their bodies and the entities they represent in phenomena. In the work done in this thesis (esp. Paper III), I examine the distinction between KLAs and ELAs, suggesting the need for finer-grained model for learning activities which involve students' bodies.

Other recent education research has examined embodiment in technology-based learning environments, such as with technologies that incorporate augmented/mixed reality (Chiu, DeJaegher, & Chao, 2015; Enyedy, Danish, Delacruz, & Kumar, 2012; Johnson-Glenberg, Birchfield, Tolentino, & Koziupa, 2014; Johnson-Glenberg & Megowan-Romanowicz, 2017) or haptic feedback (Han & Black, 2011; Schönborn et al., 2011). Lindgren et al. (2016) find that involving students' bodies in full-body interactive simulation – as compared to students using mouse-and-keyboard interfaces – can lead to an increase in students' conceptual understanding and might favorably shift the affect and motivation of these students as they learn physics. Similarly, Johnson-Glenberg et al. (2014) suggest a way to taxonomize the degrees of

embodiment in educational technology, including the criteria of (1) “motoric engagement,” (2) “gestural congruency (i.e., how well-mapped the evoked gesture is to the content to be learned),” and (3) “perception of immersion” (p. 89). After comparing students using low-embodied technology to students using high-embodied technology, the authors posit that instructional design which is embodied to the highest degree – by way of maximizing these three criteria – and which takes advantage of *collaboration*, leads to students learning more content and remembering that content longer. Such research shows promise for revealing how students’ technologically-enabled embodiment benefits their learning of science. I see my work in this thesis as also contributing to this conversation, particularly in the context of physics, by providing a moment-to-moment account of students’ embodied engagement in a technology-rich learning environment.

2.5 Summary of literature review

In this chapter, I have reviewed the historical development and the existing research areas of three relevant fields: physics education research (PER), research on instructional technology (IT), and research on language and social interaction (LSI). I have also positioned the work of my licentiate thesis and made a case for its novelty of the within and across these three fields. In relation to general PER, this thesis focuses on the advancement of theory by working across the topical areas of *Conceptual Understanding*, *Problem Solving*, and *Cognitive Psychology*, as described by Doctor and Mestre (2014) in their review. In relation to physics-relevant IT, my work contributes to the newer, understudied paradigm of Computer-Supported Collaborative Learning by focusing on students’ shared use of constructionist *Controllable Worlds* and modern *Human-Computer Interfaces*. In relation to physics-relevant LSI, this thesis embraces the embodied nature of students’ interactions and contributes to the growing body of social-semiotic research in physics teaching and learning. In doing so, I bring underused theoretical perspectives to the PER community and synthesize these perspectives together within physics-relevant contexts that other researchers can find meaningful.

3 The digital tools studied

As reviewed in Section 2.2, there are myriad digital tools developed, used, and studied within PER. For this licentiate thesis, I have chosen to focus on the subset of instructional technologies which I referred to earlier as *Controllable Worlds*. More specifically, I have studied how small groups of physics students used the open-ended, sandbox software, *Algodoo*, and the PhET simulation, *My Solar System*. In this section, I describe the features of *Algodoo* and *My Solar System* in depth, as well as discuss why I chose to study these software – in combination with an interactive whiteboard – for the purposes of this thesis.

3.1 *Algodoo* ^{II}

Algodoo (accessible at www.algodoo.com) is a two-dimensional sandbox software which was inspired, at least in part, by Seymour Papert's constructionist approach to learning (Gregorcic & Bodin, 2017). At first glance, *Algodoo* resembles other digital drawing software such as Microsoft Paint, Corel Draw, or Adobe Illustrator in that it contains various toolbars for creating objects of different geometrical shapes, colors, and sizes. However, unlike these other digital drawing platforms, *Algodoo* allows users to press play and have the user-drawn objects dynamically interact. Objects in the software will bounce off each other, roll around, swing from ropes, etc. In this way, users are able to create 'runnable' scenes from a diverse set of available construction elements within *Algodoo* – including physics-relevant elements such things as springs, axles, motors, thrusters, ropes, and fastening tools. These scenes typically contain constructions ranging from simple systems (e.g. spring-mass pendula, balls rolling down slopes, or two-body gravitational systems) to more elaborate ones (e.g. suspension bridges, cars, and engine transmission systems). When users create scenes of objects within *Algodoo* and press the play button, the scenes they have built then evolve in accordance with Newtonian mechanics in two dimensions.

However, unlike other mathematics modeling tools such as Modellus and Matlab – which feature an exposed, editable architecture – *Algodoo* is not designed for users to easily change every aspect of the rules governing the virtual world. For example, while users can turn gravity or air resistance off, the

underlying mechanics of object interaction cannot be altered from a two-dimensional Newtonian system. Indeed, some physics education researchers might see *Algodo*'s algorithmic opacity as a potential hindrance to students' learning how to model (e.g. Hestenes, 1995); however, I argue – as have other physics education researchers (Gregorcic & Bodin, 2017) – that *Algodo* retains a level of algorithmic semi-transparency which allows students to create and manipulate virtual worlds without requiring they have prior knowledge of programming. In this latter sense, *Algodo* can be seen as facilitating new and potentially beneficial experiences in a digital modeling environment for those users without fluency in coding languages (Gregorcic, 2016). In fact, other recent PER efforts have shown *Algodo* to be an intuitive-enough program for students at both high schools and universities that these students can, in a matter of minutes, start engaging in creative activities even when they use the software for the first time (Gregorcic, Etkina, et al., 2017). *Algodo*'s ease-of-access is a key component in my consideration of it functioning as a microworld for the purposes of this thesis (esp. in Paper II). The other important characteristic of *Algodo* is that it provides, through visual and interactive means, a range of dynamic representations which have been shown by research to contribute to effective physics learning (e.g. Rosengrant, Van Heuvelen, et al., 2009). In what follows, I discuss *Algodo*'s capability for representing mathematical concepts.

Representations afforded by Algodo

Algodo, like any other computer-based model of phenomena or modeling software, is built up from formal mathematical relationships in its source code. The software can track the motion of the objects created within it to be able to display quantities such as momentum, force, velocity, and position. This is due to the fact that these quantities are part of the internal structure that manifests in the external user interface (Plass & Schwartz, 2014). *Algodo* dynamically updates visual representations in real time (i.e. while it runs), which allows users to access and manipulate physical quantities describing virtual objects in ways that would be impossible to achieve in a traditional physics laboratory, a classroom, or in everyday life.⁴⁰ Nonetheless, while including these mathematical aspects, the *Algodo* environment still retains many characteristics of the world which students experience in their everyday life. In the software, users can 'grab,' move, and even 'throw' virtual objects, which can then be observed to bounce off each other, slide, tumble, and generally behave in ways that most people can relate to their everyday experiences with real-world objects.

⁴⁰ Note here that the capability to generate dynamic representations is a powerful characteristic of *Algodo* when paired with the construction-based environment, but dynamic representations are not unique when compared to the range of other *Controllable Worlds* technologies or even MBL tools.

As is discussed in Paper I and II, by including mathematical representations (e.g. Figure 4) like dynamic vector arrows (e.g. velocity, momentum and force), numbers and sliders representing values of physics-relevant quantities (e.g. density, restitution, coefficient of friction), and plots of quantities (e.g. kinetic energy vs. time, x-position vs. y-position) alongside the visually accessible virtual world, *Algodo* superimposes formal physics and mathematical ideas onto a more familiar world of physical, albeit simulated, interactions. *Algodo* provides opportunities for students to explore and engage in open-ended and creative tasks where they can experience physics-relevant, mathematical ideas in action and interact with physics content in new pedagogical ways which are not typically available. For example, students can observe the forces acting between the parts of a suspension bridge, which they may have built themselves, by selecting to display *Algodo*'s overlay of dynamically-changing force vectors on top of the bridge itself. The close interplay of the mathematical representations within an intuitively-manipulable virtual world gives students and teachers access to a rich collection of meaning-making resources. These resources can be employed to help students develop a better understanding of the meanings embedded in mathematical representations that are used in physics and may even encourage them to make use of these representations in their communication of physics ideas.

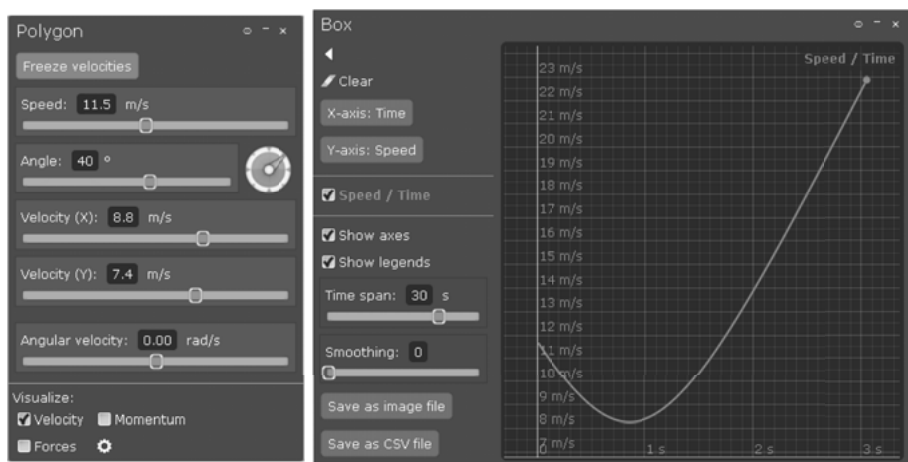


Figure 4. Two examples of the representations provided by *Algodo*, namely the 'Velocities' tab (left) and a graph from the 'Show Plot' function (right). In the Velocities tab, sliders for changing the speed, angle, velocity (x), velocity (y), and angular velocity are provided along with a wheel which displays the angle of velocity and checkboxes for displaying vectors (for velocity, momentum, and forces) on the selected object(s). In the Show Plot window, various quantities can be assigned to the axes and the options are provided to display the title ('Speed / Time' in this case), the axes, and the legends. The slider labelled 'Time span' allows the user to select the length of time to include (from the most recent 'run' of the simulation) while the slider labelled 'Smoothing' allows the user to smooth the graph of the data.

3.2 *My Solar System* ^{III}

My Solar System is a two-dimensional simulation software from PhET (see Section 2.2.2) which allows users to create circular bodies of varying masses, give them initial velocities, and observe how the created systems behave (Figure 5). In contrast to *Algodoo*, – which due to its open-ended nature, allows for a wider variety of user-created objects and dynamic touch-screen inputs – the *My Solar System* software utilizes prefabricated orbital scenarios, termed ‘presets.’ In *My Solar System*, students will typically start their exploration with one of these presets and then edit the features of the preset to see how the masses and initial velocities of the bodies in the simulation affect their dynamic motion when the simulation runs. The *My Solar System* simulation software was originally selected as an object of study (in Rådahl’s master’s thesis project (2017), as discussed in Section 4.2), in part, to examine how its preset-based structure differed from the open-ended structure of *Algodoo*. In Paper III, where *My Solar System* features in the data, I ultimately attend less directly to the students’ use of the simulation software itself. Instead, I examine the students’ interaction with each other, as set against the technologically-rich backdrop of the PhET simulation on an interactive whiteboard.

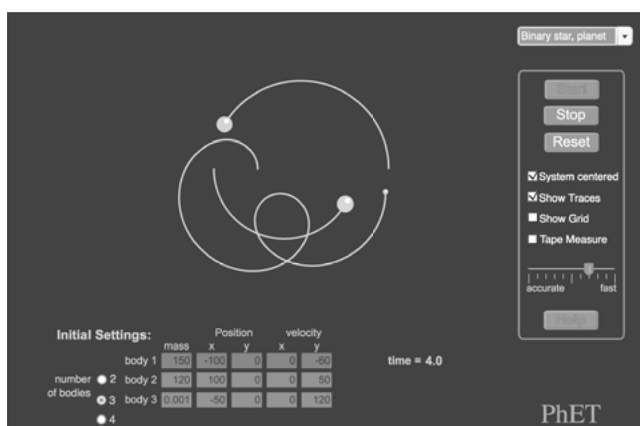


Figure 5. A screenshot of the PhET simulation, *My Solar System*, on the “Binary star, planet” preset, showing the simulation a short while after hitting the Start button (in the upper-right). The presets dropdown menu can be seen above the Start button. Along the bottom of the interface, users can enter values with a keyboard to precisely set the mass, x- and y-positions, and x- and y-velocities of the bodies in the system.

3.3 The interactive whiteboard ^{II}

The creative potential of *Controllable Worlds* like *Algodoo* and *My Solar System* appears to be significantly enhanced when used in combination with a

large touch screen, such as an interactive whiteboard (IWB) (Gregorcic, 2015a). The IWB provides students with common perceptual ground (Roth & Lawless, 2002a) which they can visually appreciate in small groups and which they can refer to using environmentally-coupled hand gestures (Goodwin, 2007; Gregorcic, Planinsic, et al., 2017). This allows students to engage with the software in collaborative exploration and communication (Mellingsæter & Bungum, 2015). As this thesis will further explore, the IWB seems to allow students to address conceptually interesting ideas even when their knowledge of corresponding vocabulary is limited. Where they struggle to find words to express meaning, they can resort to gestures, such as pointing to patterns and values on the screen (Gregorcic, Planinsic, et al., 2017). The pronounced gestural and interactional components of student communication in front of the IWB can also provide researchers with a better insight into students' meaning-making than paying attention to their speech alone. For these reasons, and because an IWB was available for use in data collection, I found it worthwhile to study the combination of the IWB with *Algodoo* and *My Solar System*.

4 Methodology

In Chapter 2, I positioned this licentiate thesis in relation to the research fields of physics education research, instructional technology (IT), and language and social interaction (LSI). In this chapter, I will provide an overview of the methodological position adopted across the three papers that make up my thesis. In doing so, I discuss the motivation for using a case-study approach to my research (comprising video-recorded data), explain the context and setup of the data collection sessions, and introduce the analytic approaches used. At the end of the chapter, I will discuss the topics of trustworthiness and ethical concerns related to my research.

4.1 Case-oriented research

This licentiate thesis is an example of case-oriented PER, more specifically case study research. In this section I explain what is meant by a ‘case-oriented’ methodology and discuss why it is apt for answering the types of research questions my thesis poses.

Drawing on the work of Greene and Caracelli (1997), Robertson et al. (2018) explain how PER can be viewed in terms of two methodological perspectives,⁴¹ namely case-oriented research and recurrence-oriented research. The names of these perspectives themselves imply something about the type of work that typifies them: case-oriented researchers tend to focus in-depth on single cases (i.e. lone instances), while recurrence-oriented researchers tend to focus on re-occurring phenomena (i.e. many repeatable instances). Nonetheless, as Robertson et al. (2018) discuss, this nominally-apparent distinction between case- and recurrence-oriented research is importantly underpinned by a difference in the sets of methodological assumptions to which each perspective implicitly adheres. As the authors state, “case-oriented research [assumes]

⁴¹ Here, Robertson et al. (2018) make use of Greene and Caracelli’s (1997) notion of a ‘methodological paradigm,’ which differs from the Kuhnian version of paradigm I utilized in Section 2.2. For Greene and Caracelli (1997), a paradigm is “a set of interlocking philosophical assumptions and stances about knowledge, our social world, our ability to know that world, and our reasons for knowing it—assumptions that collectively warrant certain methods, certain knowledge claims, and certain actions on those claims” (p. 6). For clarity’s sake – since I utilize the term paradigm in a different sense for much of Chapter 2 – I have chosen to replace Robertson et al.’s (2018) use of ‘paradigm’ with the term, ‘perspective.’

that (1) social actions are guided by the meanings that people are making of their local environments and that (2) reality is subjectively constructed” (p. 11). Alternatively, “recurrence-oriented research is predicated on the assumptions that (1) human behavior is guided by predictable relationships between variables and that (2) real phenomena are reproducible” (p. 9). Put another way, case-oriented and recurrence-oriented researchers treat the nature of human behavior and its replicability in fundamentally different ways. For physics education researchers, these underlying assumptions have bearing on what kinds of data should get collected, the methods of analysis that should be used, and the types of knowledge claims that are seen as valid.

It is worthwhile to discuss how Robertson et al.’s (2018) notion of case- and recurrence-oriented research relates to the more widely used labels of qualitative and quantitative research methods. Historically, there has been a hard-fought philosophical divide between the so-called qualitative and quantitative research traditions within academic fields such as PER. Indeed, some researchers within PER and elsewhere often identify themselves first and foremost by their answer to the ‘qualitative/quantitative’ question.⁴² Nonetheless, for the purposes of my work, I see it as most important to disambiguate qualitative and quantitative *data* from qualitative and quantitative *analyses*. For example, with qualitative data (e.g. interviews, video recordings, focus groups, field observations, etc.), both qualitative (or interpretivist) analyses and quantitative (or positivist) analyses can be carried out, sometimes even within the same study. I agree with Robertson et al. (2018) in the view that case-oriented PER (of which this thesis is an example) should be more readily understood as qualitative analyses of qualitative data. Alternatively, recurrence-oriented research is more likely to be associated with quantitative analyses, whether conducted on quantitative data or qualitative data.

In this thesis, I have been interested in exploring the socially-negotiated meaning-making of students as they utilize creative digital learning environments. As discussed in Chapter 2, this is a topic which has yet to receive significant attention in PER, especially at the intersection of PER, research on IT, and research on LSI. As such, I see my area of research as particularly open for the development of theory. In aligning myself with the methodological perspective of case-oriented PER, I side with Robertson et al. (2018) in how case-oriented research is especially suited for theoretical development.

[Case]-oriented PER seeks to broaden audience perspective by illustrating, building, and refining theories. Researchers clarify participants’ points of view, reveal and challenge implicit assumptions, demonstrate possibility, develop mechanisms that explain certain teaching and learning phenomena, and coordinate multiple modalities to better understand thinking and learning.

⁴² Recently, the zealotry of this methodological debate may have subsided somewhat (see Robson & McCartan (2016); and Russ and Odden’s (2018) discussion of alternatives for identifying one’s research in the space of PER).

Recurrence-oriented PER, on the other hand, seeks to help readers plan and predict instruction by identifying recurring teaching and learning phenomena, such as conceptual difficulties that students may encounter when learning concept x ; and instructional causes and effects, such as variables that influence learning gains and misconception-like patterns in student responses.

(Robertson et al., 2018, p. 27)

Perhaps equally important to my positioning as within case-oriented PER, it is important to note that I am interested in tracking the moment-to-moment interactions of students rather than, for example, any quantifiable shifts in conceptual understanding or epistemological beliefs measured at the end of a particular physics activity. This is not to say that I see quantifiable shifts of these kind to be of no value, but rather that, in choosing to better understand the fine-grained negotiations in student meaning-making, I have necessarily attended less to such traditionally ‘assessable’ features of physics teaching and learning. An understanding of the moment-to-moment evolution of under-researched learning environments like the ones constituting this thesis first requires that a fine-grained examination of relevant examples be conducted. Among other things, the work which I present in this thesis can provide me and other interested parties with the material for more meaningful quantitative questions to be posed around students’ use of digital tools in the process of physics learning. It is for these reasons – that case-oriented methodological perspective is apt for developing theory and aligned with my tracking of moment-to-moment interactions within novel learning environments – that I have chosen to do case-oriented research in this thesis (in the form of qualitative analyses of qualitative, case study data). The implications of this methodology, and issues of trustworthiness and ethics in case-oriented research, are discussed Section 4.4.

4.2 Data collection

In this section, I review how the data was collected for each of the three papers that make up this thesis. The data comprises three data sets in the form of video-recorded case studies, each one involving small student groups interacting around a *Controllable World* (see Section 2.2.2) on an IWB. In what follows, I will discuss how the participants of the studies were recruited, the tasks which the participants were given, and what equipment was used to carry out the data collection. It is important to note that, while the analyses for each paper in this thesis were conducted by me, it was only the first data set which was directly collected by me. The first data set was collected as a first foray into the functionality of *Algodo* in relation to the physical world, in an attempt to answer Research Question 1a. Based on the richness of the students’ interactions, I was compelled to use this data set for both Papers I and II,

eventually contributing to Research Questions 1a, 1b, and 1c. The second data set was collected before my doctoral studies began, as part of my supervisor’s (Gregorcic’s) doctoral thesis work in Slovenia. Since I was not part of the design of this data collection, I will review the details of the data collection as reported by Gregorcic in his thesis and associated publications. This second data set was adopted for use in this thesis as it was found to include a multimodally-rich case that furthered the theoretical discussion of Paper II, where I answer Research Questions 1b and 1c. The third data set was collected as part of a master’s thesis which I co-supervised with Gregorcic and which is used in Paper III. Though I did not participate in the data collection sessions for the third data set, the methods used were based on, among other things, my experience gained from the collection of the first data set. The third data set inspired me to take up the theoretically-focused Research Question 2 such that an analysis could be done for answering Research Question 3. Some pertinent details about the three data sets – i.e. the papers in which they were used, the research questions they helped answer, the *Controllable World* software studied, and the original language in which the data collection sessions were held – is summarized in Table 2.

Table 2. The relationships of the data sets, papers, research questions, digital tools, and languages used in the data for this licentiate thesis.

Data set	Used in	Research questions	Studied software (with IWB)	Original Language
1	Paper I and II	1a, 1b, & 1c	<i>Algodoo</i>	English
2	Paper II	1b and 1c	<i>Algodoo</i>	Slovenian
3	Paper III	3	<i>My Solar System</i>	Swedish

4.2.1 The first data set^{I & II}

In my initial data collection, I was first interested in exploring how sandbox-like, construction-based software was used by students in relation to the physical world. Thus, for the first data set, video recordings of student pairs were collected as they worked with *Algodoo* alongside a physical laboratory setup. The participants were pre-service teachers in an introductory level physics course at a Swedish university. Pre-service teachers at this university attend a mix of physics, mathematics, and pedagogy courses during their program. At the time of data collection, the students – who volunteered to participate in this study – were completing their first semester of physics and mathematics. I encouraged the students to sign up with another student with whom they were comfortable working, such that the pairs of participants were self-organized. This particular demographic of students was selected because my advisor and I had an amicable relationship with the teacher of their course and

because we anticipated the students' interest in becoming teachers might make them more likely to volunteer for a study around physics instructional technology. In total, the data collection comprised six participants observed pairwise on separate occasions (i.e. three occasions of two participants at a time).

The data collection took place in small room equipped with an IWB (running *Algodoo*) and a physical ramp setup positioned on some nearby tables. The physical ramp setup consisted of a straight metal ramp, a hockey puck, and several wooden blocks for incrementing the height of one end of the ramp on the table. Each session consisted of three different parts: (1) a 45-minute⁴³ portion where the participants were encouraged to explore the functionality of *Algodoo* and learn the basics of the software, (2) a 60-minute physics activity involving the physical ramp setup alongside *Algodoo*, and (3) a 30-minute wrap-up interview on the participants' impressions of using the software and the session overall. While video data was collected for the all three parts of each session, the data used in Paper I and II came from the second, 60-minute portion with the physics activity. The task given (orally) to the participants during this second part was as follows (Figure 6):

Using both the physical ramp and Algodoo, convince us (the researchers) of the relationship between (1) the height above the table from which the puck is released to roll down the inclined ramp and (2) the horizontal distance from the edge of the table which the puck travels before hitting the ground.

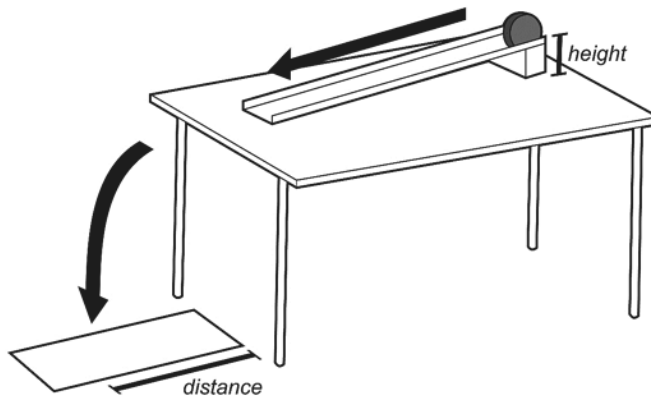


Figure 6. The physical ramp setup used alongside *Algodoo* in data set 1.

Throughout the sessions, I (and my supervisor) sat in the room with the participants to play the role of a skeptic observer, asking the participants to elaborate on their reasoning or explain what they had just done. We were also there

⁴³ All durations are approximate and varied slightly for each pair of participants.

to encourage the students to utilize both *Algodo* and the physical ramp setup to convince us of their result. Although Swedish was the participants' native language, the students were asked to they speak in English during the session so that I could follow along and respond to their interaction when helpful (I neither speak nor understand Swedish).⁴⁴

Each data collection session was recorded with three video cameras (and their built-in microphones). One camera was directed toward the physical lab setup, one was directed toward the interactive whiteboard, and was one mounted from the ceiling to capture the area around both the physical lab setup and the interactive whiteboard. The use of three cameras had a two-fold functionality: (1) to better capture the behavior students exhibited as they moved between the physical setup and the interactive whiteboard and (2) to act as a failsafe in the event of one video camera's failure.

4.2.2 The second data set ^{II}

The second set of video data was collected previously by Bor Gregorcic as part of his doctoral thesis (2015b), the goal of which was to “[advance] the use of IWBs in physics lessons and at the same time [explore] how physics teachers and learners respond to novel ways of its use” (p. 19). This thesis was carried out in a Slovenian high school where a transition to school-wide use of IWBs had occurred five years earlier. Gregorcic collaborated with two experienced physics teachers from this high school, both of whom used IWBs in their teaching.

The data which I have utilized from Gregorcic's study (the second data set of this thesis) was collected by Gregorcic to examine the use of IWBs in astronomy instruction (Gregorcic, 2015a) where small groups of Slovenian high school students used an *Algodo*-IWB setup to explore celestial motion. The students were presented a scene in *Algodo* which involved a central circular body with an attractive potential – representing a star or planet in an astronomical system. Gregorcic designed this scene – called the ‘Kepler's laws activity’ – in *Algodo* to provide students with “hands-on [access] to [the] otherwise experimentally inaccessible topic” of orbital mechanics (Gregorcic, 2015a, p. 515). The students used the *Algodo*-IWB setup to qualitatively investigate Kepler's laws of planetary motion (Gregorcic et al., 2015; Gregorcic, Planinsic, et al., 2017), specifically with the prompt to explore how relatively smaller bodies behave in the vicinity of the larger central massive body. The students drew planet-like or moon-like objects and, by swiping on the IWB, threw these objects into orbit around the star-like object located in the center of the scene. It was also possible for the students to send objects into orbit by pausing the simulation, placing the object at the desired radius away from the central circle, assigning a velocity to the object, and then running the

⁴⁴ See Section 4.4 for a discussion of languages and translation.

simulation. Some groups chose to display the force vectors or velocity vectors of the objects as these objects orbited the central object.

Gregorcic explains that “the aim of the small group study [was] to observe the affordances of [the Kepler’s laws] activity in-situ and analyze how these affordances (IWB manipulation affordances, opportunities for collaborative scientific inquiry, embodiment, etc.) [helped] students investigate Kepler’s laws” (Gregorcic, 2015b, p. 192). Two groups of three students volunteered to participate in the study:

All six participating students (group 1 and 2) [were] second year students (16 years old). Group 1 was from an intensive math class and group 2 was from an ordinary class. [Their teacher] briefed the students about the ongoing study about IWB use in physics instruction and asked if there were any volunteers that would like to participate in it. The six students that volunteered (3 from each class) attended (separately) a short introduction to Algodoo a week prior to the Kepler’s laws small group activity given by the researcher. In the introduction, he showed them the basic functions of Algodoo on the IWB and asked them to install it on their own computers and get familiar with it in the week before the activity. The introduction did not include any references to Kepler’s laws and did not even mention the possibility of exploring phenomena in a non-uniform gravitational field. Students, as was seen later, did not explore orbital motion in Algodoo prior to the Kepler’s laws activity a week later. However, they did investigate Algodoo and have shown a familiarity with its use that allowed them to use it on the IWB with relative ease.

(Gregorcic, 2015b, p. 192)

As with the first data set used in this thesis, the researcher remained present in the room with the groups of students as they interacted with each other and the *Algodoo*-IWB setup.

The researcher has provided scaffolding during the group activities, which was mostly directed towards technical management of Algodoo on the IWB. Such scaffolding increased the activity’s time efficiency and helped reduce frustration that could otherwise result in the students not being experts in Algodoo use. The researcher can therefore also be seen as a part of the groups that divided the labor during the Kepler’s laws activity on the IWB. The other role that the researcher took was that of an instructor and discussion facilitator. This way, he made sure that students addressed relevant points and did not get lost and at the same time, when necessary, asked relevant questions and encouraged scientific discourse among group members.

(Gregorcic, 2015b, pp. 192–193)

The group activities were video recorded with a single digital camera positioned across the room as the students worked.

4.2.3 The third data set ^{III}

The video data comprising the third data set were initially collected as part of a master's thesis project in PER (Rådahl, 2017) which investigated when and how responsive teaching techniques (Robertson, Scherr, & Hammer, 2015b) might be effectively applied during open-ended learning activities involving small groups of students in digitally-rich environments. Six students were recruited from a class of Swedish senior-level high schoolers, all of whom were enrolled in a three-year natural science program.⁴⁵ This particular class of students was chosen on the basis that Rådahl (a coauthor on Paper III) had spent eight weeks interacting with them during the previous year as part of his pre-service teacher education program practicum requirements. It was believed that a positive rapport had been developed during those eight weeks such that these students would be more likely to participate in the study when asked. The recruitment process involved making an announcement at the high school, where the project plan was described and the students were invited to volunteer for the study along with a friend of their choice from class. The students volunteered in pairs and each pair met Rådahl at Uppsala University for a session lasting approximately two hours.

The sessions took place in a small, otherwise-vacant room equipped with an IWB (the same room, in fact that data set 1 was collected) and involved three parts: (1) a brief introduction to the study, (2) an open-ended activity around orbital motion where participants used both *My Solar System* and also *Algodoo* (one software at a time), and (3) a brief exit interview. In the first part, as they were not experienced users of either *My Solar System* or *Algodoo*, the participants were given a short introduction to both digital environments by the researcher and then prompted with the instruction “to explore how small bodies behave around larger ones and to learn about orbital motion” (Rådahl, 2017, p. 12). The participants were explicitly encouraged to explore anything which interested them related to that topic and to share their thoughts out loud as they did so (in a 'think-aloud' manner, see Charters, 2003). The researcher remained present throughout the activity, providing technical support with the software and the IWB, offering advice on how best to use the software when the students were stuck, encouraging them to go further with interesting discussions, and occasionally requesting clarification from the students as to why they chose to do one thing or another.

The sessions were video recorded via a digital camera placed across the room as well as via screen-capture recordings from the IWB. Despite the researcher and the pair of students being the only people present in the room, the video sources were also supplemented, as a back-up measure, with an

⁴⁵ The upper-secondary school level in Sweden (gymnasieskola, roughly comparable to U.S. grade 11-12+) requires a topical focus, such as natural science or social science.

audio recording from a smartphone placed face-down on a table near the students.

4.3 General analytic approach

The analytic approach used in Papers I, II, and III is generally one of which I refer to as multimodal conversation analysis (see Section 2.4.4). As discussed in Section 2.4.3, conversation-analytic approaches tend to involve the fine-grained study of human interactions on a moment-to-moment basis. This attention to the sequence of meaning-making resources, especially when combined with a consideration for the multimodality of interactions, allows researchers – myself alike – to examine the interplay of talk, gesture, gaze, body position, etc. as they are employed by interlocutors to negotiate meaning.

The specific details of the analyses carried out in each of the papers for this licentiate thesis differ slightly from one another, especially as a consequence of each paper focusing on a particular aspect of student interaction in digitally-rich learning environments. Thus, while I have maintained a generally consistent approach through multimodal conversation analysis, the details of analysis for each paper are dealt with in the next chapter (in Sections 4.1.1, 4.2.1, and 4.3.1, respectively). In the remainder of this section, I review another key part of my analytic approach, namely the use of multimodal transcription for the presentation of data.

4.3.1 Presentation of data: multimodal transcription

Though the past use of qualitative data sources such as interview data has not automatically entailed qualitative analysis per se (see Hammer & Berland (2014), for example), those physics education researchers who do take a qualitative analytic approach with their data have tended to focus almost exclusively on the things which teachers and students *say* (as discussed in Section 2.3). Accordingly, such physics education researchers have usually involved text-based transcripts as a means of presenting data in publications. In this thesis, however, I attend to the non-verbal components of students' communication (e.g. gesture, gaze, manipulation of objects, and body posture). I do this with the view that these non-verbal features are noteworthy and necessary constituents in students' interaction (as in Gregorcic, Planinsic, et al., 2017; Samuelsson et al., 2019; Scherr, 2008; Volkwyn et al., 2018). To reflect this extension of my analytic focus beyond speech alone, I choose to present my qualitative data with *multimodal transcripts* (Baldry & Thibault, 2006; Bezemer & Mavers, 2011). In this section, I explain what a multimodal transcription entails and discuss why I have chosen a particular technique, namely that of line illustrations, for presentation of my data.

As research on language and social interaction has evolved to include multimodal aspects of communication, the traditional text-only transcriptions which focus on speech have evolved to include things like pictures, frames of video (e.g. Goodwin, 2007; Gregorcic, Planinsic, et al., 2017), and illustrations (e.g. Gregorcic & Haglund, 2018; McNeill, 1992). Transcriptions of this expanded type are now generally referred to as multimodal transcripts. The rationale behind including pictures or illustrations of speakers' body movements and positions stems from researchers' desires to include more meaning-making resources than speech alone in their analyses of language in use. Especially since the specifics of multimodal meaning-making are difficult/impossible to adequately describe in text, researchers interested in language and social interaction are able to better analyze and more clearly present multimodal data with the inclusion of pictures or illustrations. Examples of multimodal approaches in PER – which utilize multimodal transcripts in various ways and to varying degrees – can be found across several physics contexts: such as investigations of students' understanding of collisions (Scherr, 2008), orbital motion (Gregorcic, Planinsic, et al., 2017), coordinate systems (Volkwyn et al., 2018), and work/energy (Tang, Tan, & Yeo, 2011).

However, in this thesis, I make particular use of line illustrations for my multimodal transcription of data. There are several benefits to using illustrations instead of pictures or frames of video. In the following section, I examine the use of illustrations in multimodal transcripts and make a case for their increased use in PER.

The use of illustrations

I begin my discussion of illustrations by highlighting some key considerations regarding the use of illustrations for the presentation of qualitative data in academic work. I first discuss the benefits of illustrations over pictures/frames of video. Then, I examine the specific benefits of using *vector-based* illustrations as a special case. Finally, I discuss some of the potential drawbacks to using illustrations and how these drawbacks might be mitigated.

Illustrations versus pictures/frames of video

By far, the leading benefit to using illustrations over pictures or frames of video is the clarity of relevant content afforded by a less cluttered image. While a frame from a video recording may be easily interpretable by the researcher who was present in the room during filming (or who has watched the video several times during analysis), it is not necessarily the case that a newcomer to the data will reliably perceive the same level of detail in an image they are seeing for the first time. Particularly when data is collected in authentic teaching environments (or even close approximations to these environments) with common, non-cinematic lighting and backgrounds filled with people and things other than the researcher's focus, the resulting pictures or frames of video data can be low-contrast and/or cluttered. Ultimately, it can

often become difficult for a reader to glean the desired information from such representations.

Alternatively, line illustrations, especially when created with an attention to detail, can function as visual depictions of qualitative data that are neither lacking in contrast nor abundant in extraneous details. With an illustration, a researcher can quite literally outline the pertinent features of the scene in a manner which is clear and concise for the reader. In doing so, they can produce a high-resolution, high-contrast representation and avoiding the features of a scene on which the reader need not focus. Bezemer and Mavers (2011) characterize this type of practice as *highlighting* in the creation of a multimodal transcript, wherein a researcher “draw[s] the attention of their readership to elements of the focal interaction” (p. 195). While a researcher who uses pictures or frames of video must rely only on their selection of specific images as their means of highlighting in their visual representations, a researcher who uses illustrations is able to further highlight specific details and features of a given interaction.

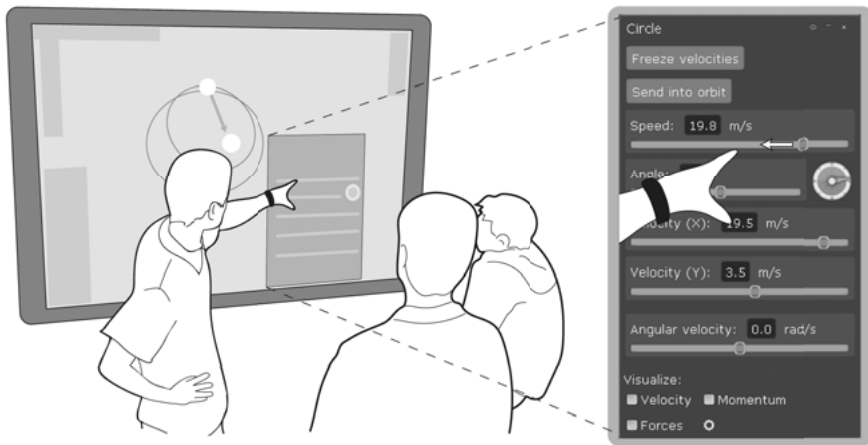


Figure 7. An example of the type of line illustration included in my multimodal transcripts, which shows the extent to which I am able to highlight with illustrations instead of pictures/frames of video (this figure is from my analysis in Paper II and is identical to Figure 10).

Furthermore, researchers who use illustrations can go beyond a simple recreation of a picture or frame of video in highlighting elements of participants' interactions. For example, in Figure 7, which is an illustration used in Paper II (see Section 5.2.4), I have inset an artificially magnified view of a menu alongside the outline of three participants in a learning environment to provide a clearer rendition of the student's gestural motion against the backdrop of *Algodoo*. It is worth noting that the magnified portion of the original scene is not only enlarged but also rotated toward the reader so that the labels and

sliders of the menu can be more easily read. While a similar ‘zooming in’ technique could be applied to a picture or frame of video by scaling up a section of the image, doing so would result in portions of the visual representation which would be lower resolution and which could not be easily reoriented as was done in Figure 7. The fine control in creating these types of visual techniques is uniquely afforded to illustration. In a way, illustrations like Figure 7 might be interpreted as semi-schematic diagrams for qualitative data, whereby a researcher can combine the abstraction and reorientation of elements (similar to ‘exploded’ 3D-engineering drawings) with a more realistic depiction of the interaction drawn to resemble a picture or video frame.

The second main advantage for using illustrations instead of pictures or frames of video is that the anonymity of the subjects can be maintained without the need for blocking of faces or facial features. While protecting the identities of those who participate in research is the norm for research on human subjects (A. Clark, 2006), doing so with pictures or frames of video generally involves obscuring the faces of the participants via an overlaid shape or some form of blurring. This generally eliminates the possibility of including the participants’ gaze or facial expressions as meaningful contributions in the visual representation. With an illustration, on the other hand, a researcher can outline participants’ faces to a level of detail which does not fully resemble the participants’ likeness but which can still convey enough facial detail to still portray things like gaze or expression. For a discussion of anonymization and ethical treatment of data, see Section 4.4.4.

The special case of vector-based illustrations

While the advantages listed above are, indeed, relevant for a variety of non-digital and digital media (ranging from scanned pen-and-paper illustrations to the more modern, stylus-and-tablet illustrations) I now highlight how a particular type of digital illustration, vector-based illustrations, have unique advantages worth noting for the multimodally-inclined physics education researcher. Vector-based images (by which I mean those images made using vector graphics rather than raster, or bitmap, graphics) are ones where the lines, shapes, and colors are defined by the mathematical relationship between points in a 2D space rather than as values per pixel. This means that creating illustrations within vector-based editors can afford a researcher two major advantages over other approaches.

First, researchers using a vector-based approach can produce high resolution illustrations at any scale. By nature of the structure of vector-based images – which are compiled in terms of mathematical curves and values associated with coordinates in a plane – vector-based illustrations do not take on any sort of defined resolution until they have been converted to a raster version for printing or embedding in documents. In the same way that the idea of the plot of $y = x$ does not have a resolution until it is portrayed on a screen or printed out, vector-based images are not forced to have any resolution until

they are saved as a raster-based file format such as JPEG, TIFF, or PNG (vector-based file formats such as SVG also exist). This can not only be a practical benefit to the researcher as they format manuscripts for printing or online publication, but can also benefit the clarity of the illustration as compared to potentially low-resolution pictures or frames of video (as discussed above).

Second, researchers using a vector-based approach can precisely edit the details of an illustration in a manner which is efficient and reversible. Since the information of a vector-based illustration is processed mathematically, the vertices and edges of shapes can be repeatedly moved and shaped. If a portion of an outline is drawn incorrectly, for example, it need not be redrawn in order to correct the error. The illustrating researcher can simply alter the erroneous segment of the outline in isolation. Especially as a researcher generates various iterations of an illustration, which should almost certainly be done if a high-quality illustration is desired, the vector-based approach can give them precise control over the digital image without all or some of the illustration having to be redrawn each time something needs updating.

The drawbacks of illustrations

Despite the many benefits of illustrations discussed above, the substitution of a drawn image for a picture or frame of video can generally be viewed as a step away from the ‘realism’ of the qualitative data (Bezemer & Mavers, 2011). Indeed, any representation of qualitative data should be seen as an interpretive account made by the researcher (with a varying degree of subjectivity, and not as data in and of itself) (Hammer & Berland, 2014). However, illustrations in particular are a more apparent indication of a researcher’s interpretation as compared to a picture or frame of video (especially when used in a manner to omit what the researcher deems to be irrelevant details). Nonetheless, Jewitt et al. (2016) point out that the creation of any transcription (with an illustration or otherwise) necessarily involves the sustaining of certain interactional factors and the loss of others. Researchers should be aware of these gains and losses that occur in the process of transcribing and attend to them for the reader in a way which addresses the departure from realism.

Another potential drawback to creating illustrations for qualitative research lies in the time it can add to the length of a project. Not only does it take time for a researcher to become familiar with the new processes and tools associated with illustrating, it also often takes more time to produce illustrations than it does to simply embed a photo or frame of video in a manuscript. Interested researchers must gauge for themselves the degree to which their transcription may capitalize on the benefits described above in order to determine if this extra time is worth spending. For example, if a researcher is able to record an interaction between participants in a properly-lit room, with few distracting details in the background, and has permission to use the participants’ faces, it is possible that a video frame from the recording would be clear enough to avoid the need of an illustration. Still, I would argue that the default position

of the modern qualitative researcher should not be one which is unaware toward illustrations but rather one which involves carefully vetting each of the images used in a publication to determine if illustrated versions of the images would not improve on their communicative power as images in multimodal transcripts.

4.4 Establishing trustworthiness and ethical integrity

In any research endeavor, the quality of results (aside from relevance or novelty) stems from the trustworthiness and ethical integrity of data collection and analysis. In this section, I review how I have controlled for these concerns in my research for this licentiate thesis.

4.4.1 Trustworthiness

First, I argue how for the trustworthiness of my licentiate work on the grounds that my methods should be seen as appropriately valid, reliable, and generalizable (to the extent that those criteria apply to case-oriented PER). Validity, reliability, and generalizability have been outright rejected by some interpretivist researchers due to their originating from recurrence-oriented, positivist research perspectives (see, for example, Wolcott, 1994). However, in this thesis, I side with Robson and McCartan (2016), Roberston et al. (2018), Guba and Lincoln (1982), and Bassey (2001) in the stance that ‘traditional’ questions of trustworthiness in positivist research can and should be answered in a manner which is adapted for the conditions and circumstances of case-oriented, interpretivist research. To this end, Guba and Lincoln (1982) pose four trustworthiness questions with which every researcher, regardless of perspective, must contend:

1. *Truth value.* How can one establish confidence in the “truth” of the findings of a particular inquiry for the respondents with which and the context in which the inquiry was carried out?
2. *Applicability.* How can one determine the degree to which the findings of a particular inquiry may have applicability in other contexts or with other respondents?
3. *Consistency.* How can one determine whether the findings of an inquiry would be consistently repeated if the inquiry were replicated with the same (or similar) context?
4. *Neutrality.* How can one establish the degree to which the findings of an inquiry are a function solely of respondents and of the conditions of the inquiry and not of the biases, motivations, interests, perspectives, and so on, of the inquirer?

(Guba & Lincoln, 1982, p. 246)

As I have suggested above, recurrence-oriented researchers tend to deal with these four trustworthiness questions by addressing the criteria of validity, reliability, and generalizability. In this thesis, I see the first and fourth of Guba and Lincoln's (1982) questions as relating to *validity*. Likewise, I see the second and third of these questions as related to the positivist criteria of *generalizability* and *reliability*, respectively⁴⁶ (see Table 3). In order to accommodate the differences in axiomatic assumptions that case-oriented research (in their words, "naturalistic inquiry")⁴⁷ entails, Guba and Lincoln (1982) define a new set of trustworthiness criteria: namely, *credibility*, *transferability*, *dependability*, and *confirmability* (respectively, in order of the questions above).

Table 3. The trustworthiness questions posed by Guba and Lincoln (1982) and the corresponding answers within the recurrence-oriented and case-oriented research perspectives. In the case-oriented column, I include Guba and Lincoln's four criteria for trustworthiness in interpretivist research in [brackets].

Trustworthiness questions	Recurrence-oriented answers	Case-oriented answers
<i>Truth value</i>	Validity	Interpretative validity [<i>credibility</i>]
<i>Applicability</i>	(Scientific and probabilistic) Generalizability	(Fuzzy) Generalizability [<i>transferability</i>]
<i>Consistency</i>	Reliability	Reliability [<i>dependability</i>]
<i>Neutrality</i>	Validity	Interpretative validity [<i>confirmability</i>]

⁴⁶ The three terms, validity, reliability, and generalizability, are not the exact terms used by Guba and Lincoln (1982) in describing how traditional scientific (positivist) research tends to address the four trustworthiness questions. Instead, the authors list "*internal validity*, *external validity*, *reliability*, and *objectivity*" (p. 246) as the criteria typically utilized to answer each trustworthiness question, respectively by number. I have opted to avoid these latter terms so that my discussion of trustworthiness can more readily relate to Maxwell's (1996) and Robson and McCartan's (2016) discussions on the topic (in addition to Guba and Lincoln's).

⁴⁷ Guba and Lincoln (1982) discuss *naturalistic* and *rationalistic* research, which I take to correspond to case-oriented and recurrence-oriented research, respectively. There is not, perhaps, a true equivalence between these pairs of terms as I use them here. Nonetheless, forgoing this terminological distinction, I argue that, for the purposes of discussing trustworthiness in my thesis, the criterion of credibility, transferability, dependability, and confirmability generated by Guba and Lincoln are useful constructs in the context of case-oriented PER.

In what follows, I discuss the trustworthiness of my research under the headings of validity, reliability, and generalizability. As I do so, I explain how I have adapted each of these (recurrence-oriented) terms for my case-oriented perspective in this thesis.

Validity

In the colloquial sense, validity refers to the degree to which something is “accurate, or correct, or true” (Robson & McCartan, 2016, p. 169). This relates to Guba and Lincoln’s (1982) *Truth value* and *Neutrality* questions. In recurrence-oriented, positivist research, the issue of validity is generally dealt with by ensuring a research outcome has *construct validity* (that the researcher(s) really measured what they thought they measured), *face validity* (that the outcome is reasonable), *predictive criterion validity* (that the outcome predicts an outside criterion), and/or *internal validity* (that a causal link can genuinely be made between ‘input’ and ‘outcome’) (see Cook & Campbell, 1979). Establishing validity in reference to these concerns allows recurrence-oriented researchers to report that a certain treatment (or set of initial conditions) caused a certain outcome. For an example from PER, Hake (1998) had to address issues of random and systematic error in the FCI while reporting that interactive engagement led to statistically better conceptual understanding across 6,500 students.

In case-oriented research like my thesis, verifying a causal link between treatment and outcome is generally not the aim. Instead, case-oriented PER tends to examine the complex mechanisms at play while students make meaning in idiosyncratic contexts. Thus, when determining if a case-oriented research project is valid, a different set of criteria than those listed above for recurrence-oriented research is necessary. Specifically, as Maxwell (1996) frames the topic, interpretivist researchers must contend with three levels of validity: *descriptive validity*, *interpretative validity*, and *theoretical validity*. Guba and Lincoln’s (1982) notions of *credibility* and *confirmability* relate especially to the second of these. In what follows, I review each type of interpretivist validity and discuss how I have dealt with them in my licentiate work.

Descriptive validity

For Maxwell (1996), the issue of *descriptive validity* relates to whether or not the data collected are accurate and complete (Maxwell, 1996). In other words, descriptive validity is the degree to which a research effort actually captures that which occurs in the case at hand. In the data for this thesis, descriptive validity relates to the question of whether or not the interaction of the students was accurately and completely captured. The ‘gold standard’ for ensuring descriptive validity is the collection of video data (Robson & McCartan, 2016). In this way, issues with observational bias (e.g. selective attention, selective memory, interpersonal factors, etc.) – which are essentially unavoidable

pitfalls associated with field notes or other researcher-subjective reports⁴⁸ – can be avoided with regards to the description of events themselves. For this thesis, the descriptive validity of the research was ensured by video recording the sessions of interest (at times, with multiple cameras and audio devices as back-up measures).

Interpretative validity (credibility and confirmability)

The issue of *interpretative validity* relates to whether or not an interpretation was unduly imposed on the data rather than emerging from the researcher's engagement with it (Maxwell, 1996). To account for interpretive validity in my research, my interpretations of the participants' interactions were regularly checked with 'outsiders' (within the research group at Uppsala) who were not working directly with the data. On several occasions, this resulted in the interpretations being questioned and updated accordingly. This is a practice referred to by Guba and Lincoln (1982) as "peer debriefing" (p. 247), which is one recommendation for safeguarding the *credibility*⁴⁹ of interpretivist research. The risk for incorrect interpretation was especially high in my treatment of the second and third datasets, as a translation was needed to analyze the data in English. In these instances, the translation was completed and verified before analysis as well as checked again after analysis to ensure that the translator could have come to the same interpretation starting in the original Slovenian or Swedish, respectively. Nonetheless, in doing case-oriented research, I also acknowledge that there is an inherent subjectivity to my analyses, which manifests as a string of personal choices and which is unavoidable (indeed, by design).

[...] when engaging in case-oriented research that seeks to construct narratives of particular classroom events, researchers make selections as they: choose when and where to record video (which entails selecting relevant populations or content); capture video (which involves pointing the camera in a particular direction); select an episode (which involves choosing a portion of the video corpus to analyze in detail); and formulate claims (which involves highlighting particular parts of the selected episode as evidence). Invention happens in this kind of research as researchers build connections between case and theory (in

⁴⁸ There are many reasons why a researcher would choose to use observer-subjective methods like field notes, despite the challenges to descriptive validity. Among these is that fact that audio/video recordings are nearly impossible to manage at the scale of an intensive longitudinal study. For an example of quality education research which utilizes participant observations and field notes as its main source of data, see Jonathan Clark's (1993) master's thesis.

⁴⁹ Guba and Lincoln (1982) define the crucial question of credibility as "do the data sources (most often humans) find the inquirer's analysis, formulations, and interpretations to be credible (believable)?" (p. 246). I would argue that the onus of judging credibility in case-oriented PER should extend to beyond the participants themselves to include the wider community of researchers and teachers who might also have experience with similar contexts.

order to articulate and refine what a particular episode is a case of), as well as when they categorize and interpret observations to formulate claims.

(Robertson et al., 2018, p. 18)

The goal in case-oriented research is, thus, not necessarily to eliminate bias entirely, but rather acknowledge where choices and interpretations have been made in an attempt to form a coherent interpretation.⁵⁰ My goal has been to use my theoretical framings (discussed in Chapter 2) in a sound way so as to give rise to analyses that represent my understanding of student interactions when seen against the theoretical underpinnings of my chosen methodology. In this way, readers and other members of the PER community can judge for themselves whether or not the interpretation conducted in this thesis has been appropriately and soundly done so as to yield a high-quality outcome.

Theoretical (perspectival) validity

For Maxwell (1996), the issue of theoretical validity, which I might also describe as perspectival validity, relates to whether or not alternative theories (or perspectives from the literature) could have been applied instead of the one(s) chosen. For this thesis, I have methodologically matched my research questions and the data collected to various theoretical perspectives. This matching was something that grew alongside the parts that make up my licentiate study as an extensive, iterative process of reading, discussion, and reflection. The decision of how best to analyze each case in this thesis was, thus, made as part of a learning-journey with the data (as is shown in Chapter 5). Still, to address the point of alternate perspectives nominally, I have included references to other possible perspectives where it has seemed appropriate throughout my analyses. Furthermore, many of the main theoretical perspectives adopted in this thesis were not presupposed during data collection at all. For example, the third data set was originally collected with the purposes of comparing *Algodo* and *My Solar System* (Rådahl, 2017). However, upon viewing the data, a combination of social semiotics and embodied cognition was deemed to be an apt fit (see Section 4.3). Robertson et al. (2018) explain that case-oriented researchers “refine, extend, and refute theories by connecting theory to specific cases, identifying what the case under study is a *case of*” (p. 16). In this spirit, I see it as one of the central tasks of this thesis to select and extend PER theory. The theoretical perspectives in this thesis are not used to the exclusion of other potentially-applicable theories, but rather as lenses which reveal particularly novel insights when used to examine cases of physics students’ interaction.

⁵⁰ To this point about biases, Guba and Lincoln (1982) recommend that the *confirmability* of case-oriented research can be increased by researchers “practicing reflexivity,” that is “attempting to uncover [their] underlying [...] assumptions, biases, or prejudices about the context or problem” (p. 248).

Reliability

A research effort's reliability can be understood as the degree to which the same procedures could be followed and produce the same findings and conclusions. In natural science research, reliability is of paramount concern for results. Likewise, in a significant portion of qualitative (but recurrence-oriented) PER – especially those projects which attempt to generate reliable coding schemes or taxonomies from qualitative data – the use of multiple researchers ('raters') to reliably affirm the same codes is somewhat standard practice (see Hammer and Berland's (2014) discussion on interrater reliability in qualitative PER). In every instance, however, reliable research must include a detailed account of procedures such that there is something to follow. Case-oriented research, if it wishes to be seen as reliable in its own way, is no exception. Even while some case studies might deal with rare occurrences that are reported precisely *because* they are uncommon, the researcher still has an obligation to adequately explain the context and procedures taken which led to the occurrence. Guba and Lincoln (1982) refer to this topic in interpretivist research as *dependability*, which they use to mean a relative stability in claims once one accounts for irreproducibility of any case-oriented project. As Yin (2009) explains, "the general way of approaching the reliability problem [in case studies] is to make as many steps as operational as possible and to conduct research as if someone were always looking over your shoulder" (p. 45). For the reliability of this thesis, I provide scrupulous detail on the context and methods of the research in the style of a "thick description" (Geertz, 1973). In this way, regardless of the reproducibility of the specific interactional phenomena I have studied, the same methods of data collection and analysis could be repeated.

Generalizability

The generalizability of a research result is the extent to which the result has predictive power in comparable situations. This is the criteria which Guba and Lincoln (1982) refer to as *transferability*, raised in response to the *Applicability* question for trustworthiness. In this thesis, I make use of Bassey's (2001) framing of the issue of generalizability in the context of education research. Bassey distinguishes between three kinds of generalization in research: *scientific generalization*, which is the kind of empirical general law in the form of "if *x* happens in *y* circumstances, then *z* will occur in all cases" (p. 10); *probabilistic generalization*, which takes the form of "if *x* happens in *y* circumstances, then *z* will occur in about *p*% of the cases" (p. 10); and *fuzzy generalizations*, a term which he coins to refer to claims like "if *x* happens in *y* circumstances, then *z* may occur" (p. 10). Bassey's argument is that, while positivist procedures rely on scientific generalization as nearly-necessary and probabilistic generalization as a passable alternative, the third category of fuzzy generalizations is, in fact, a viable and desirable outcome for education

researchers. Fuzzy generalizations, when accompanied with careful descriptions of the context and variables, allow teachers and other researchers to “consider to act in the same way” (Bassey, 2001, p. 11). As with the reliability of case-oriented research, this resembles the advice given by Geertz (1973) that researchers develop ‘thick’ descriptions of the context of a study, such that the readers can picture themselves in the data and relate to particular aspects. I remind the reader that the goals of case-oriented research can be quite different than recurrence-oriented research:

[...] if one seeks to reveal and challenge implicit assumptions, one need only deeply study a single (detailed) instance that contradicts a standard assumption. (The goal in doing so is to refine the assumption, not simply to demonstrate the contradiction.) Likewise, to demonstrate possibility – e.g., to show that a type of interaction is possible or that a type of learning can happen in a science classroom – only requires a single instance.

(Robertson et al., 2018, pp. 27–28)

Robertson et al.’s quote here, which mirrors the sentiment of Bassey’s fuzzy generalizability, mentions the usefulness of revealing when something *can happen*. In this thesis, I take Robertson et al.’s (2018) advice in an effort to demonstrate the *possibility* of previously-unreported learning mechanisms. I show how certain events may happen during students’ interactions. In doing so, I aim to further nuance the theoretical discussion around students’ moment-to-moment use of *Controllable Worlds* in physics teaching and learning.

4.4.2 Ethical considerations

Ethical guidelines and ethical codes – such as the Declaration of Helsinki (in the case of medicine) – provide formalized steering documents by which researchers can be held ethically responsible while dealing with potentially sensitive data. However, as Johnsson et al. (2014) argue, the existence of “ethics review and guidelines are insufficient to ensure morally responsible research” (p. 30) in themselves. This is to say that, while ethical standards might provide researchers with a concrete list of ethical rules, it is ultimately up to each researcher to morally follow those rules and/or to act in a morally responsible manner *beyond* those rules in potentially ambiguous contexts. As some researchers point out (S. Eriksson, Helgesson, & Höglund, 2007; Johnsson et al., 2014), deciding which ethical rule is apt for a specific research situation requires *moral* judgement. Thus, for the purposes of this thesis, I took the moral position that my participants should be afforded the highest degree of individual respect, especially in regard to their privilege to control how, when, and for what purposes they are recorded. Moreover, I acknowledge that I have a responsibility as a researcher to safeguard any personal data that I collect in a manner which reduces the chance of malicious repurposing of that data. In

this section, I discuss how I have attended to various ethical standards which are expected in social science and humanities research (and, thus, also PER).

Still, as I have conducted my research in Sweden, I have also complied by the guidelines and regulations set by the Swedish Research Council (2017) – and, in the time since 2018, the latest requirements as per both Swedish and European Union (EU) law (see the subsection on General Data Protection Regulation below). The relevant Swedish law – specifically the Act concerning the Ethical Review of Research Involving Humans (SFS 2003:460)⁵¹ – states that “research that does not use personally sensitive data (3 §) and does not entail physical encroachment, aim to affect subjects physically or psychologically, or entail an obvious risk of harming subjects (4 §) is not to be reviewed” by an ethical review board (Swedish Research Council, 2017, p. 15). My licentiate work has satisfied these conditions (for not requiring an external review by an ethical board) in that I have not collected *personally sensitive* data⁵² and insofar as the data collection I conducted did not pose a threat of physical or psychological harm to any of my participants.

Nonetheless, though my research did not undergo any external ethical review process, I still took the necessary steps (as per the Personal Data Act and the recommendations of the Swedish Research Council) to treat all of my participants in a morally responsible manner. To illustrate the way that I did this, I now explain the ethical measures taken in this thesis to ensure the responsible treatment of potentially sensitive data: namely, the obtaining of informed consent, the pseudo-anonymization of data, and the secure storage of data. At the end of this section, I also briefly discuss the significant new ethical regulation which was passed in the EU in 2018.

Informed consent

First, in an effort to treat the participants of my study ethically, I (and the other researchers who collected data used in this thesis) took measures to ensure that the participants were adequately informed of the expectations of their involvement as well as the process of how I would treat the data following collection. This was achieved by providing the participants with three written documents: (1) an outline of the study and the conditions of participation, (2)

⁵¹ Accessible with the following link: www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/lag-2003460-ometikprovning-av-forskning-som_sfs-2003-460.

⁵² Personally sensitive data includes information on race, ethnic origin, political views or religious conviction, and information on judgments in criminal cases (as described by the Swedish Research Council, 2017), all of which I have avoided in my research. However, through my use of video data, my research *has* involved the handling of ‘personal data.’ Thus, I have complied with the Personal Data Act (SFS 1998:204): that is, I have obtained informed consent from participants, encoded the links between recordings and personal data, and stored video data in a secure manner.

a pre-participation consent form, and (3) an extended consent form to be completed following participations.⁵³

In the first of these forms – titled “Participation in a study of the use of digital technology in physics” – I outlined the context of the study (i.e. the Division of Physics Education Research in which I study, the focus of my project, etc.), the role that participants would play in this study, the ramifications of participation (i.e. that data will be collected during the study and this data may be used in scientific publications), and the specifics of how data would be treated once collected. To the latter point, it was explained that any transcriptions or written records of the data would be anonymized and any personally identifying information (such as names, addresses, phone numbers, or any other information that would connect the participants to the study) would be kept separately from the transcriptions as well as any publications. Since the information collected would include video data, it was explained that anonymization would be enacted by censoring the faces of participants. Finally, it was explained that all data collected would be archived in a secure way according to Swedish ethical research law. This form served as an informational guide for those interested in the study and was distributed to the participants several weeks before any data collection sessions were held.

The second form – “Consent to participation in a scientific study” – was a written consent form that reiterated the content of the first form and included a place for participants offer consent by means of their signature. The signing of the second form took place immediately preceding the data collection and the students were informed that they were able to withdraw from the study at any time (during or after the session itself).

The third form – “Additional consent to use of uncensored video” – was given to the participants after the data collection was completed, asking them, now that they were aware of the things they had said and done during the preceding session, to consent to the use of uncensored video in publications using the data. Options were provided for consent to (1) fully uncensored use of the participant’s likeness, (2) partially censored use of the participant’s likeness (specified be them), or (3) fully censored use of the participant’s likeness (as per the previous consent forms). The main motivation for issuing this third form was to allow me to use the participants’ faces (if necessary) in the presentation of data which might involve facial expressions or gaze. However, as I discussed in Section 4.3.1, I ended up utilizing line illustrations for the presentation of my data and this allowed me to include the facial expressions of participants while maintaining a degree of anonymity.

⁵³ Blank copies of each of the ethical forms discussed in this section (which I used in my collection of the first data set) are included in Appendix A. In Appendix B and C, I include the consent forms utilized by Gregorcic (in Slovenian) and Rådahl (in Swedish) for the collection of the second and third data sets, respectively.

Anonymization

For the purposes of anonymizing the data collected for this thesis, I have assigned each participant with a pseudonym or code (e.g. ‘S1’ for Student 1) during transcription. The consent forms, in which the participants included their names and signatures, are kept separately in a physical folder. Since it is technically possible for the identities of the participants to be retrieved by matching the raw video files with the consent forms that contain their names, the anonymization of this data is better categorized as *pseudo-anonymization*. Nonetheless, in an effort to best protect the personal data of the participants, personally identifiable information – such as the participants’ names and faces – are avoided in the presentation/publication of data.

Storage of data

In order to ensure (as best I can) that the raw data collected for this thesis is not accessed by someone outside the research group at Uppsala, I choose to store the data on a remote hard drive which is not accessible over the network. In this way, the only time that a remote digital attack could access the data is when I am actively reviewing the data with the hard drive plugged in. The hard drive is kept in a room which remains locked, accessible only by members of the Uppsala Physics Education Research team and administrative/janitorial staff.

General Data Protection Regulation

In 2018, the EU implemented the General Data Protection Regulation (GDPR) for the safeguarding of personal data and privacy for individuals within the EU and the European Economic Area. This is a wide-reaching policy which will certainly affect the ethical rules for research in the future. The data used in this thesis was collected before GDPR was implemented, so the set of ethical rules which I followed predates this new regulation. Nonetheless, as universities across the EU – such as Uppsala University⁵⁴ – are deciphering what it means for research to be GDPR-compliant, I am keeping myself updated with new policy decisions and ensuring that the data used in this thesis always abides by these new ethical standards (while continuing to follow my moral standards for the acceptable treatment of research participants).

⁵⁴ In the time since GDPR was passed, each Swedish university (down to the level of each department) has had to interpret the new regulations in the best way that they can in order to generate descriptions of the required steps that each researcher shall legally take. At the time of writing my thesis, this is currently still an ongoing process at Uppsala University.

5 Analysis and discussion of cases

In the previous chapter, I discussed the methodological position taken in this licentiate thesis, particularly in regards to the methods used to collect the three data sets. In this chapter, I discuss the details of selection, transcription, and analyses of the three papers that make up this thesis. Beyond presenting the analyses of this thesis, this chapter also displays the progression of my licentiate work across three papers. I began my research with a short paper (Paper I) aimed at exploring how students made use of *Algodoo* on an IWB. This first analysis had to fit within a manuscript with a four-page limit, and, thus, short sections of transcript are briefly discussed. Thereafter, I was able to present longer sections of transcript in the next paper (Paper II) and the depth of my analysis increased accordingly. Finally, with the last paper (Paper III), I was able to examine the interaction of students at the greatest depth and involving the most complex analytic lens. The growth in my licentiate work is most apparent in the analyses presented in this chapter. The analytic arguments for each paper, as well as the discussions that follow, are taken in turn here – beginning with Paper I and ending with Paper III. A synthesis of the findings and implications across all three papers will appear in Chapter 6.

5.1 Paper I

As discussed in Chapter 4, Paper I involved the first data set, wherein I studied how a pair of students used *Algodoo* on an IWB alongside a physical laboratory setup. In particular, I was interested in seeing how *Algodoo* could be seen to function as a semi-formalism for the students (discussed in Section 2.4.2). Though the idea of semi-formalisms was proposed several decades ago (diSessa, 1988), there have been very few attempts to explore the idea as it manifests in students' interactions. Thus, in Paper I, I was interested in how students' multimodal interactions could be used to reveal the degree to which a software like *Algodoo* was functioning as a semi-formalism. As discussed in Section 2.4.2, I combined the idea of semi-formalisms with Hestenes' (1992) notion of Newtonian modeling games. In doing so, I was able to structure my analysis of the students' interaction around three domains: the physical world (the physical ramp setup), the semi-formal world (the construction-based environment in *Algodoo*), and the formal world (the mathematical

representations included in *Algodo*). For the purposes of this analysis, I treat the graphs within *Algodo* as part of the formal domain because they convey information through mathematical resources that physicists use to model phenomena (specifically, a coordinate system). In what follows, I review how the data was selected for analysis, explain how it was transcribed, and finally present the analysis itself from Paper I.

5.1.1 Selection of data

With approximately nine hours of video data collected, it was necessary to first select segments of video and generate a transcript of the participants' interactions. I began by watching the video recordings of all three sessions to review what had occurred. Having been present in the room with the participants during data collection, I also had an initial impression of the video data which I used to select a pair of participants. Specifically, I had found that the students from the second session of the three (which I refer to as S_a and S_b ; the researchers are denoted with 'R') had displayed a relative abundance of gestural activity as well as an ease moving between the physical ramp and *Algodo*. Thus, I chose to focus on this group in particular. For ease of viewing all of the video sources simultaneously, I used Adobe Premier Pro to combine the recordings into a single, multi-angle composite video which displayed all three video sources side by side.

5.1.2 Transcription¹

To analyze the students' actions during the session, I generated a multimodal transcription (Baldry & Thibault, 2006) of the video in which I explicitly notated the students' talk, gesture, and interaction with objects (akin to Goodwin's (2007) "environmentally coupled gestures"). I began the transcription process by viewing the video data of the second session several times all the way through, both by myself and with my research colleagues, before selecting short episodes that seemed to contain interesting activity from the standpoint of communication of physics ideas and modeling processes. Once identified, these short episodes were then watched several more times by themselves and multimodal transcripts were created using a standard text editor.⁵⁵ In a table, three columns were devoted to each student (one for logging the students' talk, one for logging gestures, and one for logging interactions with the environment) and two columns were devoted to logging the interjections of the two researchers present during data collection. Though much of this transcript did not make it into Paper I, the production of a detailed account of the students' interaction in this manner helped me interpret the most

⁵⁵ For all of the analyses presented in this licentiate, dedicated transcription software such as InqScribe and NVivo were not available for use at the time of transcription.

meaningful, short exchanges pertinent to semi-formalisms and modeling. In the following section, I have highlighted three specific exchanges. The full transcript generated from this data set can be found in Appendix D.

5.1.3 Analysis and discussion ¹

For the analysis in Paper I, I tracked how the students came to understand the ramp-puck situation by moving between three domains within the activity: namely, the physical ramp, the two-dimensional scene within *Algodo* (where the students created digital objects and had them dynamically interact), and mathematical representations of motion (in this case, x - and y -position graphs generated within *Algodo*). That is, I followed how students created and interpreted the two-dimensional model they created in *Algodo* from a multi-modal perspective to track how each of these three domains was involved in their process of meaning making. Before reviewing three instances of students moving between these domains, I briefly review the general progression of the students' activity during the session for context.

The students involved in the study were eventually successful in mathematically relating the two variables from the prompt (i.e. height of one end of the ramp above the table and distance along the floor which the puck traversed) through their use of both the physical ramp setup and a digital model within *Algodo*. Their digital model in *Algodo* was made up of an angled rectangle corresponding to the ramp, a horizontal rectangle corresponding to the portion of the table extending after the ramp, and a circle which was allowed to roll down and across the two rectangles before landing on the 'ground' (which, in *Algodo* constitutes an automatically-generated infinite plane). The students began the activity by creating the digital model to check their intuitions about the physical situation. They explored how there was a point where tipping the ramp-rectangle to a larger angle with respect the horizontal resulted in the puck travelling a shorter distance along the floor, since the puck would bounce more at the transition with the table-rectangle.

After having explored the phenomenon in *Algodo* for a short time, the students then decided to utilize the physical ramp setup. They began rolling the puck down the ramp and off the end of the table for varying ramp steepnesses. The students then plotted their results on a hand drawn graph (initial puck height vs. distance travelled before bouncing from the end of the table) to interpret the shape of the function in the range of smaller ramp angles – that is, before bouncing off the table caused diminishing returns.

In what follows, I highlight three exchanges that occurred during the students' construction of the digital model to highlight instances where the students moved between the three domains to make meaning. Each exchange is shown with an illustration of the scene (traced from the video frame), the transcribed talk that occurred during the exchange, and a diagram to illustrate which of the three domains were utilized by the students for making meaning

(where ‘Ph’ represents the physical domain, ‘S-f’ represents the semi-formal domain, and ‘F’ represents the formal domain).⁵⁶ In each of these examples, the students were not explicitly directed by the researchers to incorporate multiple domains.

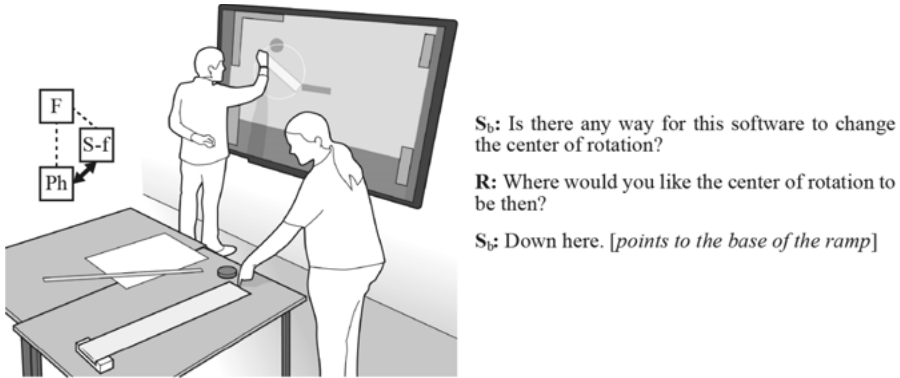


Figure 8. An exchange where S_b used the bottom of the physical ramp to explain the position around which he wanted a rectangle in Algodoo to rotate (showcasing movement between the physical domain (Ph) and the semi-formal domain (S-f)).

Figure 8 shows an exchange during the first steps of the digital model construction. The students had set up the objects in the model and were trying to determine how to rotate the tilted rectangle around its corner rather than its center (the center being the default for rotations in *Algodoo*). S_b then asked if there was a way to achieve this rotation in *Algodoo*. When one of the researchers asked where the student desired the center of rotation to be, S_b replied by pointing to the end of the physical ramp instead of the corner of the rectangle within *Algodoo*. This example showcases a student using the physical domain to elaborate a point within the semi-formal domain.

⁵⁶ In doing so, the figures included in this transcript make use of a minified version of the semi-formal modeling diagram from Section 2.4.2 (Figure 3, p. 44).

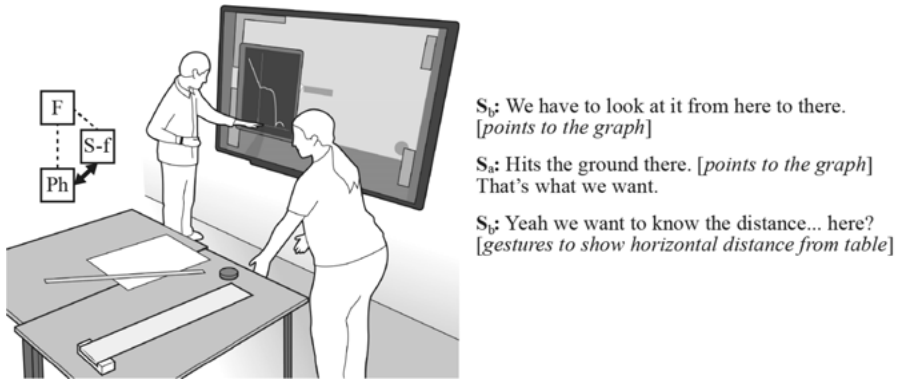


Figure 9. An exchange where S_b used an environmentally-coupled gesture to clarify one of the relevant distances for the prompt while trying to interpret a plot of the moving circle's position in *Algodo* (showcasing movement between the physical domain (Ph) and the formal domain (F)).

Figure 9 shows an exchange after the students had created the digital model and were trying to track the horizontal distance that the circle travelled before hitting the ground within *Algodo*. To do this, the students generated a plot of the y -position vs. the x -position of the circle. However, as the students interpreted their plot, they wanted to move the location of the y -axis ($x = 0$) so that they could read off the x -value directly as the horizontal distance. To clarify which distance they were attempting to measure, S_b proceeded to gesture next to the physical table while he posed a question to the researchers.

This exchange showcases an example of a student using the physical domain to make meaning in the formal domain of the graph (note again that, in these examples, both the formal domain and the semi-formal domain are accessed through *Algodo*; it is not the presence of the software or the IWB that determines the domain but rather the manner in which the software and IWB are used).

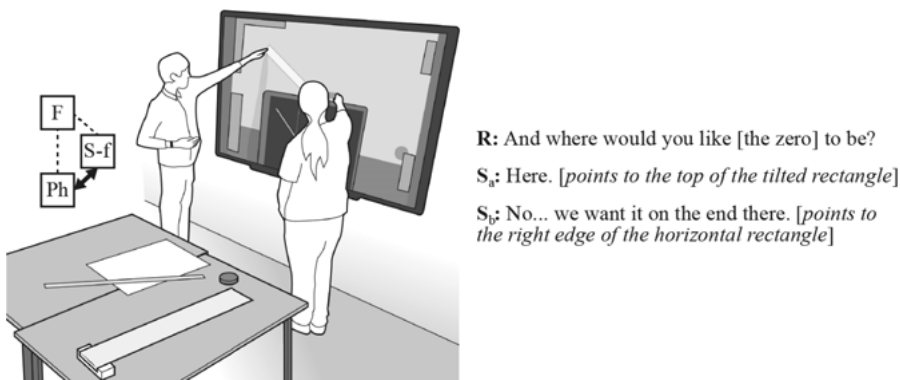


Figure 10. An exchange where both S_a and S_b point to locations within the *Algodo* scene to demonstrate where they wanted to align the y -axis ($x = 0$) in a graph they had generated (showcasing movement between the semi-formal domain (S-f) and the formal domain (F)).

Figure 10 shows an exchange shortly after the exchange in Figure 9 where the students were deciding where to place the y -axis of their graph within the *Algodo* scene so that they could read off the horizontal distance from the x -value directly. As the students determined how to move the axis of the graph, the researchers asked them where they would like the axis to be within the plot. The students both pointed to positions on the rectangles in the digital model where they thought the ideal position for the y -axis of their graph would be. This exchange showcases an example of the students using the semi-formal domain to explain their reasoning about an aspect of the formal domain.

In each of the examples shown above, the students clarified their reasoning by moving between domains. That is, when faced with a question about their digital model in *Algodo*, for example, the students answered by pointing to a distance in the physical ramp setup. By tracking the moment-to-moment meaning-making of the students in the form of talk and environmentally coupled gestures, the instances where the students were articulating their reasoning across domains is made visible. This type of attention could be paid to other sets of data in order to track the degree to which students move between the domains during a physics activity. Perhaps most interestingly, this type of analysis could be used to compare students' movement between the physical and formal domains with and without the presence of digital tools like *Algodo*. In this way, the degree to which a particular tool acts as a semi-formalism for certain students could be articulated and, thus, provide insight into the roles that the tool might play in physics learning. For example, I might propose the following hypothesis to be tested in the future:

The inclusion of creative digital learning environments (like Algodoo) in physics activities increases the likelihood that students will draw conceptual parallels between the physical world and the formalisms used in physics.

This hypothesis, whose exploration would surely aid in understanding the degree to which digital environments can be leveraged as semi-formalisms, might be tested in further empirical studies by observing how students recruit and interpret mathematical formalisms during physics activities when *Algodoo* is included as compared to students who use other more typical (single-phenomenon) simulation software and/or no digital environment at all. In the progression of this licentiate, the work done here in Paper I can be seen as first foray into studying students use of *Algodoo* on an IWB. The techniques and insights gained from this short study are expanded on in Paper II and III.

5.2 Paper II

The goal of Paper II was to explore the extent to which *Algodoo* could be seen as acting as a microworld for students through their multimodal interactions. As discussed in Section 2.4.1, definition of microworld adopted for this thesis is a user-subjective one (Rieber, 1996). Thus, in Paper II, I examined the extent to which the ‘microworldiness’ of *Algodoo* could be observed during students’ use of the software in small group work. As discussed in Section 4.2, Paper II makes use of the first and second data sets. In fact, the same group of students that were used in Paper I were selected from the first data set.⁵⁷ This case was studied in addition to the second data set in order to reflect on how *Algodoo*’s potential microworldiness might provide students with alternate, informal means for engaging with formal (mathematical) ideas. In the sections that follow, I review what it means to learn physics informally, how and why the data were selected, how transcription was carried out, and finally the analyses of the two cases themselves.

5.2.1 Informal Physics Learning ^{II}

Before presenting the analyses of the cases, it is useful to review the idea of informal physics learning, as it features in the interactions of the students studied in Paper II. By mastering the different representations used in physics (Van Heuvelen, 1991), physicists can employ a diverse range of mathematical tools such as force vectors, motion diagrams, and graphs to conceptualize phenomena in terms of formal physics models and to appropriately solve problems (Hestenes, 1992). Through their commitment to internalizing how nature is

⁵⁷ This is perhaps not surprising when one considers that a single, interactionally-rich case can reveal much about theory and methodology when viewed through various lenses.

described by their discipline, physicists cultivate, among other things, a mathematically-enhanced perspective of the phenomena that they encounter. However, and perhaps not unexpectedly, this is not necessarily the case for most students while they learn physics. For students who are not adequately familiar with – or at least not confident in – the formal, mathematically intensive concepts of physics, the techniques used by physicists to describe the world are often not readily compatible with the students' daily experience of phenomena. There exists for such students a significant difference between how they perceive the world and the way in which physics canonically represents it using formal mathematics. Indeed, students' difficulties with navigating this difference is a common point of interest for physics education researchers, found for example, in McDermott et al.'s (1987) famous discussion of students' difficulties when attempting to interpret kinematics graphs and relating them to their real-world counterparts.

In response to the sometimes-unnavigable disparity between the physical world and the mathematics which physicists use to describe it (in Paper I, described as the physical and formal domains), many students make use of other means than a direct application of mathematics. This can be seen in students' informal cultural exposure to speed and speedometers from cars. Today, the notion of a speedometer can be called upon by physics students as they make sense of velocity and acceleration, something which was impossible for either Galileo or Newton to do in the time before speedometers were invented. Students who grow up in a culture where the enforcement of speed limits is a common occurrence, where a car's top-speed is listed in advertisements, and where they can ride in a car with an omnipresent visual display of their speed, have a corpus of informal experiences which they can and, certainly do, involve in their reasoning with physics concepts such as velocity and acceleration.

In his book *Mindstorms*, Papert (1980) argued that the informal learning culture surrounding students is what provides them with the necessary *materials* with which they can construct their understanding of the world and incorporate them into their understanding of formal physics models. Thus, when the topic of velocity is discussed in a physics context, students from a speedometer-rich culture need not first conceptualize the idea of 'speed-in-general' to begin to become familiar with the concept in the formal physics sense. Such students are able to come to the physics classroom already equipped with the materials from their culture (in this example, their experiences around speedometers) with which they can build new understanding. Surely it should be noted that, as with any previously-constructed understanding that students bring to a physics classroom, an everyday experience with speedometers neither certifies that students will automatically intuit physics, nor does it ensure that students will contextualize their understanding of kinematic quantities in the manner consistent with the discipline of physics (Trowbridge & McDermott, 1980, 1981).

Nonetheless, in Paper II I explore how, as an environment rich in mathematical representations, *Algodo* can provide resources to students which might act in a similar manner to the speedometer, providing them with access to materials which they can recruit in the construction of their own understanding of physics. I suggest that when combined with appropriate instructional approaches, *Algodo* can not only afford students with experiences of mathematical ideas as they are used in physics but can also provide an environment for students where they are able to engage in playful inquiry and draw on mathematical representations in a spontaneous and non-threatening way. Similar to how speedometers can be used as materials for conceptualizing velocity and acceleration in a physics context, the carefully crafted mathematical representations provided within *Algodo* can be spontaneously recruited as rich materials in students' inquiry into physical phenomena.

5.2.2 Selection of data ^{II}

While the physics content varies between the two cases selected for this paper (namely, from the first and second data set discussed in Section 4.2), I use both cases to reveal the manner in which the presence of representational options within *Algodo* led students to coordinate their discussion and creative inputs around complex mathematical representations in ways which I interpret as appropriate for the learning of physics. These two cases were selected due to the fact that they displayed instances of creatively linking mathematics and physics through their informal use of mathematical representations. To reiterate, the original aim of the first data set collection was to examine how students used *Algodo* in combination with a physical setup (Paper I). However, in both this first data set and the second, I found short examples of students engaging with a variety of mathematical representations in novel ways. I saw the students coordinating their physical observations and mathematical ideas within *Algodo* in a manner that suggested the digital environment encouraged the meaningful use of mathematical representations.

5.2.3 Transcription ^{II}

In order to present the data in a manner which captures both the speech of the students and also their gestural activity, Paper II includes a multimodal transcript comprising written excerpts of talk⁵⁸ and line illustrations drawn from frames of the video data (which are occasionally augmented by closeups of the relevant *Algodo* menus). Each line of the transcript is numbered and labelled with the speaker or actor responsible for the speech or action contained in the line ('S1' to 'S5' for Student 1 to Student 5, respectively; and 'Re'

⁵⁸ The data collection session for Case 1 originally took place in Slovenian but we have translated the speech into English for the purposes of this chapter.

researchers). Expanding on the transcription style from Paper 1, actions such as gestures or manipulations of the IWB are included as *italicized* text in [brackets] and represented visually by illustration when useful. In the section that follows, each excerpt of transcript is followed by a summary of the what was said and done by the students to make explicit the things I wish to highlight from the students' interactions.

5.2.4 Case 1: Vector-sense with the 'Velocity' tab ^{II}

Selected data for Case 1

The first case examined in Paper II involves an excerpt from data set two, wherein a group of three students – who I refer to as Student 1 (S1), Student 2 (S2) and Student 3 (S3), along with the researcher (Re) – were recorded while they used the 'Kepler's laws activity' in *Algodoo* on an IWB (explained in Chapter 3). The excerpt begins shortly after the students had tried to send an object into orbit around the central body (the Sun) by setting the object's initial velocity within the 'Velocities' tab in the drop-down menu while the simulation was paused. The students estimated the initial conditions (radius and velocity) necessary to send the object into orbit by comparing these conditions to that of an already orbiting object from before. They pressed the play button and then watched as the newly launched object collided with another object that was already orbiting the Sun. The collision sent the new object out of the frame of view and pushed the original object into a new orbit around the Sun. While the new object was sent out of the frame of view, its Velocity menu remained open in the *Algodoo* window. I include sections of the transcript here to illustrate the informal exploration that took place after the students observed the collision.

- 1 **S2:** Okay...
- 2 **S1:** Aha!
- 3 **Re:** What happened now?
- 4 **S1:** This one's trajectory changed, but it remained constant.
- 5 **S1:** And it's losing speed.
- 6 **S2:** No, it's not losing speed.
- 7 **S1:** [*points to the slider for speed*] (Figure 11)
- 8 **S1:** One of them is losing speed.
- 9 **S2:** Yeah, yeah. That one.
- 10 **S1:** Yeah, that one, yeah. That one that is going away.
- 11 **Re:** Ah, now you're looking at that one!

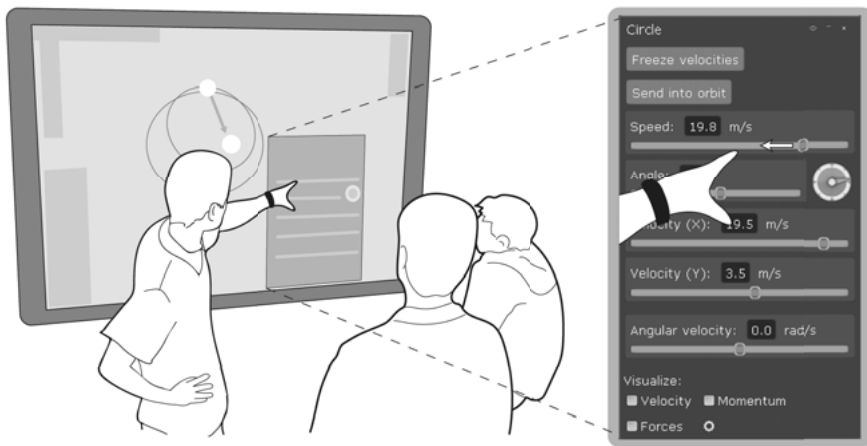


Figure 11. Student 1 (left, with Student 2, middle, and Student 3, right) is shown pointing to the moving slider labelled 'Speed' within the Velocity tab as he emphasizes that one of the objects is "losing speed" (line 6).⁵⁹

Excerpt summary: In this exchange, the students were beginning to make sense of the behavior of the two objects after the collision. They express how the originally-orbiting object had been pushed into a new, stable orbit – which Student 1 refers to as being "constant" (line 4) and which I interpret to mean stable in time (self-repeating on a closed trajectory). Noticing how the Velocity tab was displaying a decreasing speed, the students quickly came to realize that the Velocity tab was still showing data for the runaway object, which was now out of sight, past the edge of the view in *Algodo*.

(continued from above)

- 12 **S3:** Turn its angle, so it will come back.
 13 **S1:** [laughs]
 14 **S2:** [starts dragging the Angle slider to the right, changing the angle at which the runaway planet is travelling]
 15 **Re:** You can also turn the little wheel if you want to turn the angle. There, on the right side.
 16 **S1:** And let's add some speed... Or not. It's already coming back! [performs a U-turn gesture in front of the IWB] (Figure 12)
 17 **Re:** So, you noticed something interesting.
 18 **S1:** So, now it's slowly coming back into orbit. Because it's becoming faster. [points to the speed slider, where the value is increasing]

⁵⁹ It should be noted that the values for Speed, Angle, etc. in the Velocity tab are an approximate recreation for the illustration and do not necessarily reflect the exact values seen by the students during the session (no screen capture was available to determine these values as they appeared on the IWB). Also, in absolute size these values are 'unrealistic' for objects on planetary scales, yet their usefulness holds in their proportions to one another and their qualitative changes over time.

- 19 **S3:** Yes.
 20 **S2:** Yes.

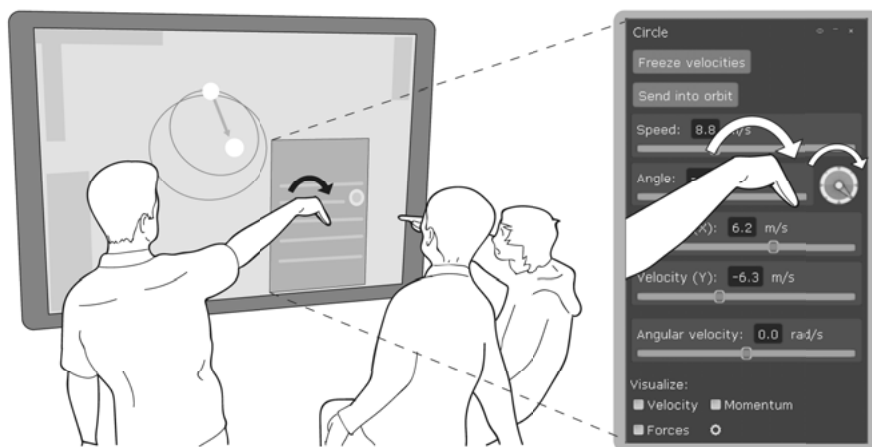


Figure 12. Student 1 is shown gesturing in front of the IWB with a U-turn gesture (downward) as he vocalises that the runaway planet is “already coming back” (line 16). Student 3 points toward the wheel of the velocity menu as it turns with the changing trajectory of the planet.

Excerpt summary: Here, Student 3 suggested that they “turn [the planet’s] angle” (line 12) in order to bring it back into sight. Student 2 then dragged the Angle slider to the right to change the angle at which the planet was traveling, prompting the researcher to suggest that Student 2 could have also used the Wheel to change the angle. After Student 2 changed the angle, Student 1 initially wanted to alter the object’s speed as well, but changed his mind as he watched the angle spontaneously rotate with the motion of the planet. He interpreted the changing angle as the planet reversing direction and he gestured with his hand in a U-turn motion (Figure 12). He also noticed that the Speed slider was moving to the right, which he interpreted as meaning that the object’s speed was increasing. He explained this as the object “slowly coming back into orbit” (line 18) and the other two students agreed.

(continued from above)

- 21 **Re:** Coming into orbit, what does that mean?
 22 **S3:** Closer...
 23 **S1:** Closer to the [Sun].
 24 **S2:** Actually, it is already kind of in orbit, unless it will crash into it. Because it... because it is attracting it. It means it will... [*starts gesturing a large curve in the air*]
 25 **S1:** Just a moment. Considering it was travelling away from this object and it was losing speed...

- 26 **S2:** Yes, it was.
 27 **S1:** And there was no resistance...
 28 **S2:** It was in orbit from the beginning, but...
 29 **Re:** Okay. Okay. Interesting observation. It was flying away. It was losing speed.
 30 **S2:** It was losing speed and it had no resistance.
 31 **S2:** Yes, but that's normal. If you have a body out here and a gravitational force between them, and there is no other force, and you don't accelerate [the body out there], its speed will get smaller until it will turn around and travel the other way. [*mimics the motion of a planet moving away from the Sun and then back toward it with his hand*] (Figure 13)
 32 **S2:** Which is interesting, but... I mean, it's interesting...
 33 **S1:** Yeah, I get it.

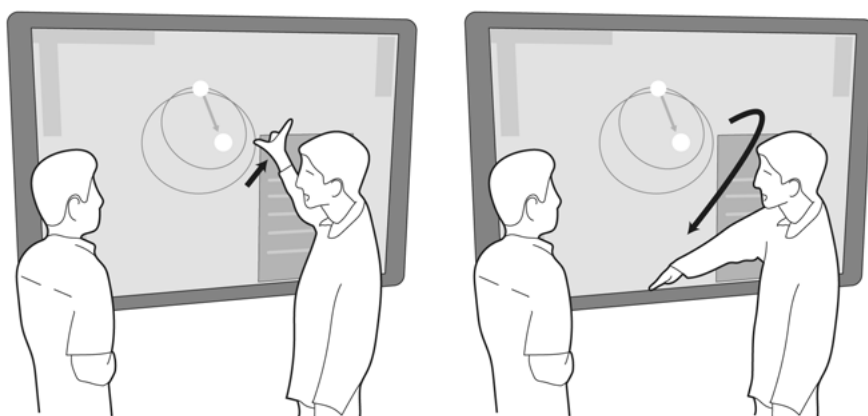


Figure 13. Student 2 is shown gesturing to show the movement of a planet as it is accelerated by the Sun. I interpret this explanation as one that uses a Newtonian model of Sun-planet interaction.

Excerpt summary: Here, the students engaged in a discussion about orbital motion and the underlying mechanisms that govern the changes in an object's velocity. Though Student 1 initially had an issue with the slowing-down of a planet in a frictionless environment, Student 2 was able to explain how the object's behavior made sense in a system with gravitational force (line 31, which I interpret as a Newtonian perspective). Student 2 supported his argumentation with environmentally-coupled hand gestures, symbolizing the movement of the planet and the direction of forces (Figure 13).

(continued from above)

- 34 **S1:** Aha, okay, now its angle started changing, which means... [*starts repositioning himself in front of the IWB, pointing to the Velocity tab*] (Figure 14)

- 35 **In:** Oh, yes, now you are observing that body just through [the Velocity tab].
- 36 **S2:** Yeah, um... Good point.
- 37 **S1:** [laughs]
- 38 **S2:** [uses the Zoom tool to zoom out, revealing more of the space around the Sun]
- 39 **S1:** Here it is. [notices the runaway planet on the left side of the Sun, close to the edge of the screen]
- 40 **S2:** It's here. [pointing to the runaway planet]
- 41 **S1:** Let's do it by hand.
- 42 **S2:** Let's zoom out more. Can we zoom out more?
- 43 **S1:** No.
- 44 **In:** This is the most zoomed out it can be.
- 45 **S1:** Quickly. [turns the angle wheel CW, in the direction toward the Sun]
- 46 **S2:** But now we are changing its things again.
- 47 **S1:** [drags the speed slider to the right and the planet starts traveling faster toward the Sun]
- 48 **S2:** It is going to crash directly into it.
- 49 **S1:** [adjusting the direction using the angle wheel] So now it is already growing. [watches as the speed slider spontaneously moves to the right]

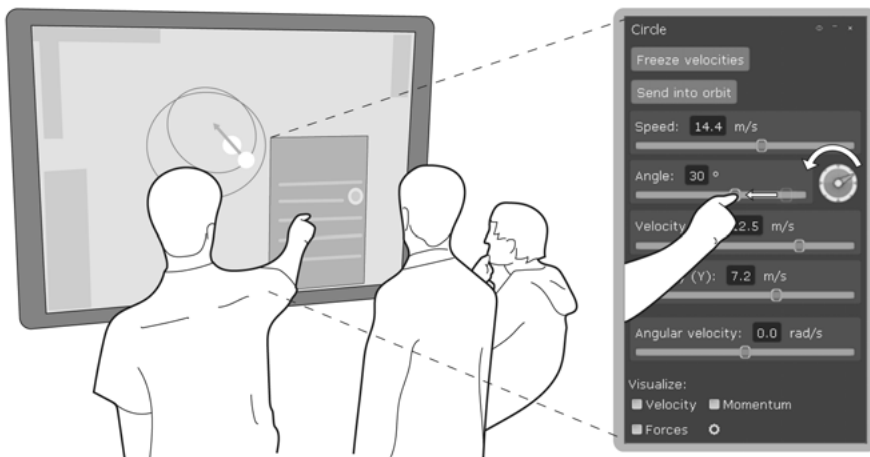


Figure 14. Student 1 is shown noticing the changing velocity of the runaway object in the Velocity tab. He repositions himself in front of the IWB and points to the changing Angle slider.

Excerpt summary: Again, Student 1 can be seen noticing an increased rate of change in the object's angle of velocity by watching the Velocity tab, all while the planet remained outside the field of view in the scene. The researcher pointed out that the students were interpreting the motion of the planet through looking at the values in Velocity tab, to which the students responded by zooming out to find the object (now on the left side of the Sun) just as it was about

to fly out of the field of view. Student 1 quickly manipulated the object's velocity by changing the angle (turning the wheel counterclockwise toward the Sun) and then increasing its speed (by dragging the Speed slider to the right). Finally, Student 1 watched the object and the Velocity tab simultaneously and noticed that the Speed slider continued to move to the right as the object accelerates toward the Sun (Figure 14).

In the excerpts of transcript presented above, it can be seen that, although the students originally speculated that the runaway object was lost after the collision, they noticed that the velocity of the runaway object changed in a way that suggested it would return if they kept waiting (meaning that the runaway object was in some type of orbit). Despite the object being absent from the frame of view in *Algodoo*, the students were able to track the motion of the object through the Velocity tab still open from before the 'play' button was pressed. They watched the Speed slider move and the Angle wheel rotate, interpreting them to understand that the runaway object was slowing down and turning back toward the Sun. The students were then able to propose explanations (which I identify as consistent with a formal, Newtonian model)⁶⁰ for the patterns of motion seen in the Velocity tab. In the end, they located the runaway object in a zoomed-out field of view and manipulated its velocity so that it started to move back directly toward the Sun.

Analysis and discussion of Case 1

The case included above is an example of how a group of students creatively used one of the representations within *Algodoo*, namely the Velocities tab, in a playful, unconventional way – which was still meaningful from a physics learning perspective. From this case, I discern two functions for which the students used the Velocity tab: (1) as a tool for manipulating (or setting) the velocity of an object and (2) as a representation which was recruited in making sense of the motion of an object.

The first function of the Velocity tab – i.e. as a tool for manipulating the velocity of an object – can be seen initially when the students used the Velocity tab to put a newly-created object into motion (giving the object an initial velocity before hitting play). Once the collision had sent the object far away from the Sun, the students then used the Velocity tab to manipulate the object's motion dynamically (with *Algodoo* running). This manipulation appeared in two instances within the data above: first, as Student 1 changed the angle of the object's velocity (line 14) and again when the same student redirected the object toward the Sun (lines 45-49). In both of these instances, the presence of *Algodoo*'s Velocity tab, which allowed Student 1 to set and manipulate the velocity of the object with sliders and a wheel, provided an opportunity for the students to engage with the orbital task creatively. More

⁶⁰ This type of interpretation here of the students' reasoning, especially in how it 'resembled' a formal idea used by the physics discipline, is something I explore further in Paper III.

traditional approaches to the learning of orbital motion often do not provide such a means for interacting with objects' velocities as they relate to orbits. In this case, the students were able to test their own ideas of orbital mechanics, giving them ownership of the result, all while they utilized a mathematically-rich interface. The manner in which the Velocity tab was used as a dynamic tool for the manipulation of velocity showcases the first concrete example of *Algodoos*'s microworldiness: the software seems to have provided the students with mathematically-rich materials, while also allowing the students to be creative and self-directed in their activities.

The second role that the Velocity tab played in the presented case was that of a representation recruited in making sense of the motion of an object. During most of the excerpt, the Velocity tab served as a monitoring device for the orbiting object outside the field of view of the *Algodoos* scene. Formally, the velocity vector of an object in two dimensions can be expressed in terms of a speed and angle (magnitude and radial direction) or as the sum of the x - and y -components of the velocity. Interestingly, in the *Algodoos* environment, the students sent an object into motion and observed its components directly, interpreting the motion of the runaway object intuitively as they tracked the changes in the angle and speed. Thus, even without being prompted to discuss vector magnitudes or components, the students were able to demonstrate some degree of fluency in vector-sense for two-dimensional motion. The presence of the Velocity tab allowed the students to spontaneously move between a familiar, informal experience of motion (the visual movement of the object on the IWB surface) and a mathematized representation of motion (within the sliders and wheel of the Velocities tab). Indeed, the limited field of vision in *Algodoos* – which made the students unable to watch the object's motion as they would normally – along with the persistence of the Velocity tab – which provided them with a dynamically updated rendition of the runaway object's velocity data – encouraged the students to interpret and make creative use of the mathematical representation made available by the software.

Though the significance of the dynamically-changing information on the Velocity tab was not initially understood by the students, as they began to make sense of what was happening, they were able to interpret the motion of the runaway planet from the controls in the tab, translating the information of the sliders and wheel into more familiar, everyday language of gesture and speech. This can be seen when the students noticed one of the objects "losing speed" (line 5), after which Student 1 started making sense of the changing angle and slowly-increasing velocity of the runaway planet with an explanatory gesture (line 16). Student 1 re-interpreted the information within the Velocity tab with a gesture, transforming the meaning carried in the software into a dynamic mode of expression (in a process of *transduction*⁶¹). He then

⁶¹ Transduction can be thought of as the process of re-expressing the meaning from one semiotic resource system to another (e.g. describing a picture in words or gesturing the motion of

engaged with the Velocity tab as a source of information about the motion of the runaway object until he was able to demonstrate his interpretation of what was going on in a more conceptual way.

Beyond functioning in the two ways described above, the *Algodo*-IWB learning environment was successful in encouraging students to spontaneously produce an explanatory model for the patterns of motion. This can be seen when Student 1 questioned the motion of the runaway object (line 25). Student 2 responded by proposing an explanation for the patterns of motion consistent with a Newtonian model of orbital motion (line 31). Student 2's interpretation of the patterns seen on the Velocity tab gave rise to explanatory talk and gesture about the behavior of orbiting objects in general. In this way, the Velocity tab within *Algodo* appears to have behaved as a point of departure for further inquiry, providing some mathematical materials which students were compelled to observe and explain in a science-like discussion (as discussed in Etkina, 2015; Gregorcic, Planinsic, et al., 2017).

This can be taken to demonstrate, in a slightly different manner, how *Algodo* can act as a microworld for students. That is, the students were inspired by the setup and the activity to not only explore and create within the mathematically-rich environment, but to also begin taking science-like approaches to solving the problems they encountered (Gregorcic, Planinsic, et al., 2017). Consequently, an argument could be made for how microworlds like *Algodo* can offer alternative ways to promote both the learning of nuanced content knowledge at the intersection of mathematics and physics and also the adoption of the behavioral patterns used by scientists, all while promoting active engagement and creativity.

I have shown here with Case 1 that, when using *Algodo*, students can use mathematical representations in a creative way, therein becoming inspired to discover how a physical system works. The students' use of the mathematical materials provided by *Algodo* was both playful – due to *Algodo*'s open-ended, creativity-driven structure – and meaningful for their understanding of the physics formalisms that underpinned the activity. It is precisely this richness of the digital environment, the way in which *Algodo* is an explorable sandbox populated by mathematically-rigorous representations, that seems to have made possible the unique, meaningful interaction presented above.

Indeed, in the case presented here, the particular affordances of *Algodo* that resulted in students' meaningful use of mathematical representations were paired with an instructional strategy of open-ended – but task-based – inquiry and exploration with some guidance from a teacher. Throughout the activity, the researcher engaged with the students to help direct them in their

simulated object with a hand movement, etc.). This process has been recently explored as a central part in students' meaning-making around physics concepts (e.g. Volkwyn et al., 2019, 2018). Nonetheless, while the case studies in my licentiate thesis could readily adopt transduction as a key process, I do not take up the topic for the sake of brevity.

exploration. If the students had simply been given the Kepler's law scene without any instruction or guiding activity, it is possible that they not have ended up manipulating the velocity in such fruitful ways. Nonetheless, for the purposes of this analysis, it is worthwhile to recognize this case as an instance where the microworldiness of *Algodo* contributed to a group of students' creative inquiry, while at the same time engaging them with formal representations of motion.

5.2.5 Case 2: Kinematics with 'Show Plot' ^{II}

Data for Case 2

I now present the second case from Paper II to illustrate the potential for *Algodo* to promote creative and meaningful use of mathematical representations. This case, which was selected from the first data set, focuses on a pair of students that used *Algodo* in an activity alongside a physical ramp and a hockey puck on a table (see Section 3.3.2). The particular excerpt of transcribed data that I present here shows how one pair of students, now referred to as Student 4 (S4) and Student 5 (S5), used the 'Show Plot' tool to quantify aspects of the puck's motion in a virtual model of the ramp-puck setup they had created. This excerpt illustrates how the students were able to recruit and interpret graphical representations in *Algodo* as they attempted to quantify a physics phenomenon.

My presentation of the data starts as Students 4 and 5 finished setting up a virtual model of the ramp-puck experiment in *Algodo*. They place two rectangular objects (representing the ramp and the table) and the circular object (the puck) in such a spatial arrangement that when they press the play button, the puck rolled down the ramp, continued off the table, and then hit the ground below (Figure 15). The students then tried to address the prompt (i.e. to relate the height above the table from which the puck was released to the distance from the end of the table to which the puck would traverse) by finding a way in which they could measure the distance the puck travelled horizontally from the edge of the table before hitting the ground.

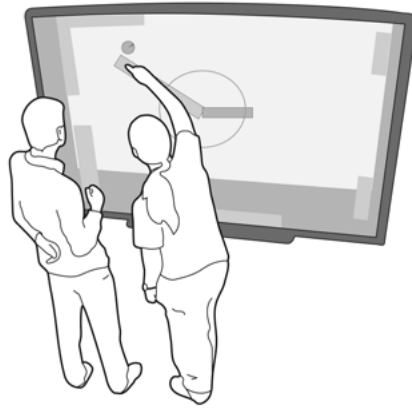


Figure 15. Student 5 (right, with Student 4, left) is shown rotating the ramp portion of the ramp-puck model to the desired angle. Here, the horizontal rectangle functioned as a virtual table, the tilted rectangle functioned as a virtual ramp, and the circle functioned as a virtual puck. In this scene, as opposed to the scene in Case 1 of Paper II, the ground was represented by a horizontal plane toward the bottom of the screen and gravity acted vertically downward.

After constructing the virtual ramp-puck setup, the students ran the scene to check the function of their model. The circle successfully rolled down and off the rectangles before hitting the ground. The students had an immediate desire to measure the distance that the puck travelled from the edge of the horizontal rectangle, but *Algodo* does not include a purpose-built distance measuring tool. Student 4 soon stumbled upon the Show Plot tool. He opened the tool and explored its options for representing plots of various physical quantities related to the selected object (the virtual puck in this case) in the form of a two-dimensional graph. He discovered that *Algodo* allows you to choose to plot different quantities on the horizontal and vertical axis of the displayed coordinate system.

- 50 **S4:** [sets the vertical axis to 'Position (y)' and then the horizontal axis
to Position (x)]
- 51 **S5:** [drags the corner of the graph window to make it smaller and then
moves the window to the left so they can watch the circle's motion
as it rolls down the ramp]
- 52 **S5:** Something like that.
- 53 **S4:** And start?
- 54 **S5:** Yeah.

Excerpt summary: In the first part in of the excerpt, the students were observed to be looking for a way to quantify the movement of the puck, in particular, to put a numerical value on the distance the puck travelled off the edge of the table. By exploring the options provided by *Algodo*, the students discovered

the Show Plot tool. Student 4 then interacted with the plotting tool to select the appropriate axes labels (the x -position and y -position of the virtual puck) and Student 5 positioned the graph window in such a way that the two of them could simultaneously observe both the virtual experiment and the plot.

(continued from above)

- 55 **S4:** *[presses the play button and they watch the puck move with the data being drawn in the graph window simultaneously]* (Figure 16)
- 56 **S5:** *And let's see. If we look closer at this... [leans in to examine the graph]*
- 57 **S4:** *Here. [points to the point on the graph corresponding to where he thinks the circle hit the ground]*
- 58 **S5:** *Yeah there. [pointing to the same point as S4]*
- 59 **S5:** *We can see that we have to look at it from here. [touches the point on the graph which he interprets as where the circle left the table] to there. [touching the point on the graph corresponding to where they agreed the circle hit the ground]⁶²*
- 60 **S4:** *Hits the ground there. That's what we need to get.*
- 61 **S5:** *Yeah, we want to know the distance here? [gestures to show the length from the end of the physical table in the room and looks to the interviewers for confirmation]*
- 62 **In:** *Mhm.*
- 63 **S5:** *Yeah. Uh... [pauses for a long time to examine the graph]*

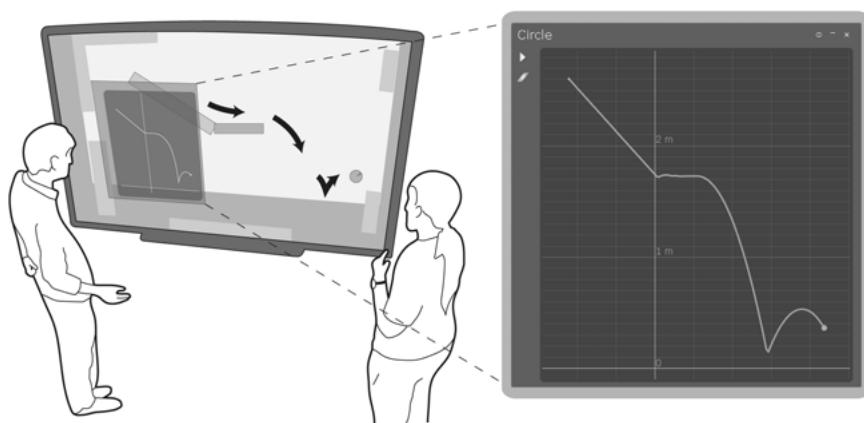


Figure 16. The students are shown examining the scene after watching the circle roll down the ramp and off the table. The graph displays a plot of the circle's motion.

⁶² This line and the next two were originally studied in Paper I (Figure 9, p. 79).

Excerpt summary: In the second part of the episode, the students ran the simulation and noted its outcome by observing the movement of the puck, as well as the self-drawing graph in parallel. They continued by then interpreting the graph. They started to relate characteristic points on the graph to spatial locations in the *Algodo* scene, as well as in the physical experiment that was set up in the room next to the IWB. They identified the distance of interest in the physical setup and then pointed out what they interpreted as the corresponding distance on the graph.

(continued from above)

- 64 **S5:** I'm trying to figure out why is there a zero here? [*points along the y-axis of the graph*] 'Cause we started way up here [*points to the upper left corner of the graph*] and where does this graph place the zero? How does this software determine where the origin is?
- 65 **In:** Mhm. Is there a question?
- 66 **S5:** Uh, I think so, I'm not... [*drags the corner of the graph window to make it larger*] I don't really know how to look at this graph to determine... I mean here it says ten meters, there. [*points to the rightmost label of the x-axis*]
- 67 **In:** So, what is this graph displaying really?
- 68 **S5:** The y-position [*gestures up and down the IWB*] and the x-position. [*gestures left and right along the IWB*] (Figure 17)
- 69 **In:** Mhm.
- 70 **S5:** But what I can't really see is where the x-position zero point is. That should be there. [*points to the origin in the graph window*] But it doesn't show much more [*taps around in the graph space to see what selecting the axes does then traces the graphed path of the ball in the plot to select various data points*]
- 71 **In:** Can you say from the graph where the x-position zero is? [*pauses*] So, this graph, what does this graph represent? Like in other words, what would you say this graph represents? 'Cause you can have velocity versus time graphs. You can have x versus time graphs but this is a y versus x graph.
- 72 **S5:** Yeah it describes exactly where the ball has been. It shows the path of the ball.
- 73 **In:** Mhm! So, in space, right?
- 74 **S5:** In space, yes.
- 75 **In:** So, I think you can actually see where the x-zero is then.⁶³
- 76 **S5:** Yeah when it starts rolling on the other one... [*grabs the graph window and drags it out of the way of the ramp*] When it starts rolling on that one. [*points to the intersection of the ramp rectangle and the table rectangle*] (Figure 18)

⁶³ This line and the next two were originally studied in Paper I (Figure 10, p. 80).

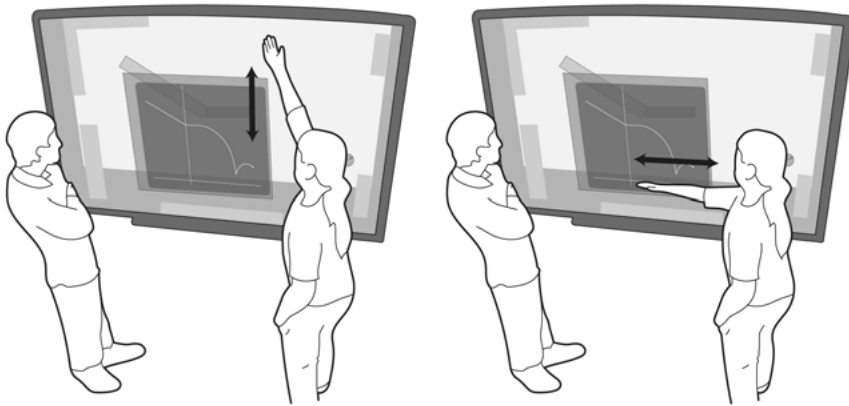


Figure 17. Student 5 is shown gesturing to describe what each of the axes is displaying. He describes that the y-axis displays the y-position of the circle (gesturing up and down) while the x-axis displays the x-position of the circle (gesturing left and right).

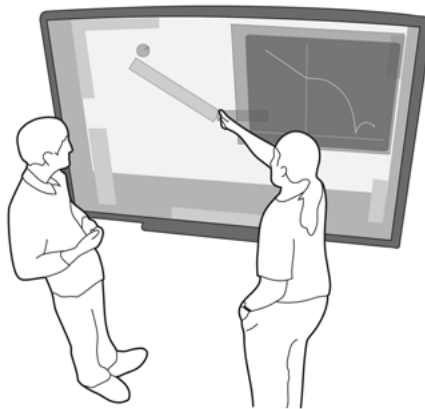


Figure 18. Student 5 is shown pointing to the intersection of the ramp rectangle (the tipped rectangle) and the table rectangle (the horizontal rectangle) to indicate the location in the scene which he interprets as the position of the $x = 0$ line of the graph.

- 77 **In:** And where would you like it to be?
 78 **S4:** Here. [points to the top right corner of the tilted rectangle]
 (Figure 19, left)
 79 **S5:** No [drags the graph window out of the way]. We want it on the
 end there [points to the end of the horizontal rectangle] (Figure 19,
 right)

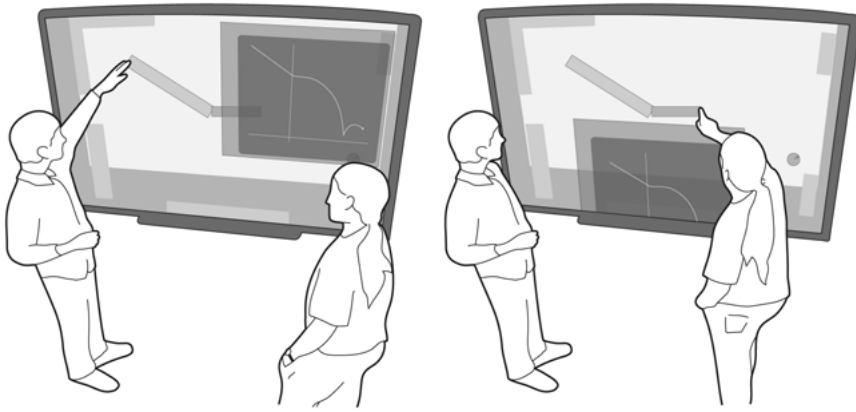


Figure 19. Student 4 is shown pointing to the position he thinks would be best for the $x = 0$ position at the top of the tilted rectangle (left image). Student 5 disagrees and points to the point he thinks they should place the $x = 0$, at the end of the horizontal rectangle (right image).

Excerpt summary: In this exchange, the students tried to make sense of the position of the origin of the coordinate system used to describe the position of the puck. The researchers encouraged them to interpret from the existing plot of the puck's motion where the origin (zero) was placed and where they would like it to be, instead. Student 4 proposed that the desired placement for the zero of the x -coordinate would have been the edge of the table (due to the convenience of reading off the distance from the edge of the table at which the puck first hit the ground). After line 79, with some technical help from the researchers, the students repositioned the objects in *Algodo* so that the right edge of the horizontal rectangle (the virtual table) was positioned at $x = 0$. This was required since *Algodo* does not allow the user to move the origin of the built-in reference frame, which is fixed to the background of the scene.

(after positioning the virtual set up as desired)

- 80 **S4:** [presses start and watches as the ball rolls down again, tracing a path on the graph similar to the one before, but with the axes re-position as they wanted]
- 81 **S5:** [presses pause] Then we can find... [traces finger along the data in the graph from top left to bottom right, stopping where the circle hit the ground] the x -position! Point seventy-five meters. (Figure 20)

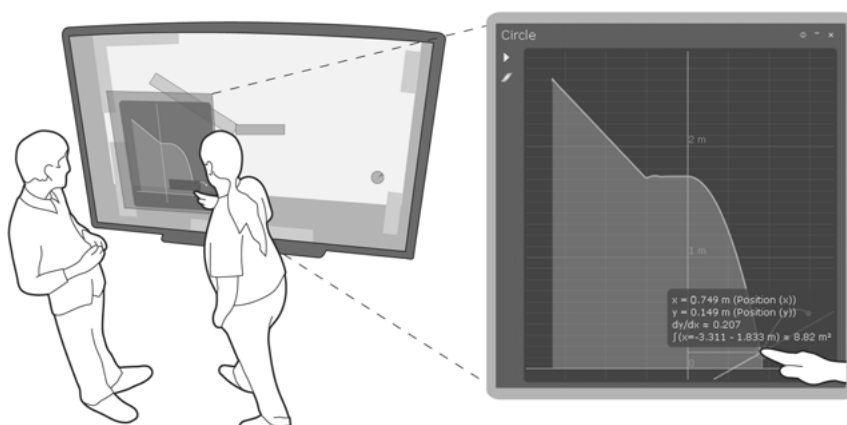


Figure 20. Student 5 is shown tracing the data in the graph (of the shifted set up where the y-axis is more conveniently placed) with his finger until he finds the point where the circle hit the ground. He is then able to read off the value for the horizontal distance from the x coordinate of the dynamic graph label.

Excerpt summary: In this last excerpt from Case 2, the students managed to assign a numeric value to the horizontal distance the rolling puck travelled before it first hit the ground. They did this by touching the location in the graph where the tracked object (the virtual puck) appeared to have first bounced and then reading the x-value of its position from the built-in graph examining tool (Figure 20).

In the student dialogue from Case 2, I present how the students stumbled upon the Show Plot tool in *Algodo* and then tried to figure out how to place the origin of their graph in a useful position for their measurement purposes. In order to figure out how to move the axes to where they wanted, the students first had to interpret what the graph was showing so that they could understand how *Algodo* had placed the origin for them (the origin is fixed by default to the background in *Algodo* and they had to move their virtual set up so that axes were aligned with the desired part of their ramp-puck model).

Analysis and discussion of Case 2

In Case 2, the students engaged with the *Algodo*-IWB setup to mathematize the motion of a puck via a graph. Despite the physics content being different from that in Case 1, I use the students' interaction in Case 2 to highlight how *Algodo* appeared to act as a microworld by providing the students with mathematical material to draw upon in a meaningful, if slightly unconventional, exploration of a physics phenomenon.

With the Show Plot tool in *Algodo*, the two students in Case 2 made use of a graph in a somewhat atypical manner: that is, to *measure* the horizontal distance travelled by the puck after leaving the table within their *Algodo*

scene. Similar to how they might have used a meter stick to measure the physical distance that the puck travelled in the non-virtual ramp-puck setup, the students used a graph within *Algodoo* to plot the position of their virtual puck (the circle) and read off the x -value from this graph as the x -component of its plotted motion. This implementation of the graphical representation is interesting in that the students measured a quantity *with* the graph rather than populating the graph with data measured by another tool. This is made possible in digital environments like *Algodoo* due to the fact that these programs are necessarily built up from mathematics. *Algodoo* was already tracking the position of the circle in relation to the background of the scene so, for the students in Case 2, it was simply a matter of finding a way to display the position of the circle in a graph for their use.

However, the students' imaginative use of the Show Plot tool still required them to employ the mathematical representation *correctly*. Initially, in order for their graph to display the position of the circle, the students first had to select the appropriate quantities for each of the axes. Student 4 chose axes labels of Position (y) and Position (x), changing them from the default labels of Speed and Time. In this way, even though *Algodoo* generated an option for graphical mathematical representation for the students, they were still required to engage with the representation enough to responsibly select an appropriate version of the graph for their given situation. The students had to tailor the mathematical representation so that it could be used in their unconventional implementation. This is the first example from Case 2 of how the microworldiness of *Algodoo* allowed the students to use mathematical representations in a creative, yet meaningful manner: the software provided the students with mathematical materials in the form of a graphical tool, which they implemented in their own creative problem solving.

The other way in which *Algodoo*'s microworld-like behaviour appears to have afforded unique opportunities to the students is in how it constrained their actual construction of a model of the ramp-puck setup. While the transcript above focuses on the students' use of the Show Plot tool, the students' mathematization within *Algodoo* began even before the excerpts of line 50, when the students *geometrized* the ramp-puck setup into the virtual space. The students first had to interpret the parts of the physical experiment (the ramp, the table, and the puck) as simple geometrical entities, spatially organized in the *Algodoo* scene so as to result in a simple geometrical model of the experiment. This meant that the students needed to make creative, physicist-like decisions about how to simplify the three-dimensional problem into a two-dimensional collection of simple shapes.

Furthermore, as the students overlaid the graph of the circle's motion in the *Algodoo* scene, they then needed to *interpret* the interactions of the objects within their model in terms of how they related to the mathematical representation. In his choice to plot the horizontal and vertical position of the circle in a graph, Student 4 effectively produced an abstract, mathematized version of

the puck's trajectory. However, since the graph did not display some of the main visual features of the scene itself (i.e. the ramp rectangle, the table rectangle, the circle, or the ground), the students were presented with the challenge of interpreting how the plotted data related to the virtual ramp-puck model. For example, the location of the edge of the table, which was particularly important for determining the distance of interest, was not explicitly represented in the graph itself. This led the students to explore the connection between the mathematical representation and the phenomenon which it represented. They did this by first running the simulation and then realizing that the axes of their plot were not where they wanted. Eventually, the students were likely able to relate specific points of the graph to places in the virtual setup in part due to the proximity and simultaneity of the representations (as is discussed in work such as Ainsworth, 2006).

I show in Case 2 how the Show Plot tool, while being used as a quantification tool for measuring horizontal distance, also involved the students in a purposeful coordination of a geometrical representation (the virtual ramp-puck model) and mathematical representation (the graph) of a physical experiment (the real ramp-puck setup). As I showed with Case 1 of Paper II, the student activity in Case 2 around the given prompt showcases how users of *Algodo* can make creative, yet meaningful use of the representations within the digital environment. The students were creatively engaged not only as they explored a novel physics phenomenon, but also as they generated a geometrical model of a real experiment. They were involved in the tailoring of a mathematical representation of motion and, by creatively leveraging the affordances of the *Algodo*-IWB setup, they were able to determine the desired distance and continue with their task. This suggests that such *Algodo*-IWB setups might be used for a variety of tasks, by a variety of students, to support student creativity and fluency in formal and mathematical representations of physics phenomena.

5.3 Paper III ^{III}

Gregorcic, Planinsic, et al. (2017) provide an analysis that shows how small groups of students described patterns, proposed experiments, and predicted outcomes in a science-like manner, all while using “hand waving,” manipulations of a large touch-screen, and informal vocabulary. Their study provides an example of students producing qualitative descriptions of orbital motion akin to Kepler's laws, showing that non-disciplinary meaning-making resources can manifest conceptual and procedural ideas that are worthwhile from a physics disciplinary perspective.

However, while Gregorcic, Planinsic, et al. (2017) illustrate how students can arrive at *descriptions* of orbital motion through spontaneous, informal means, in Paper III, I explore how students might recruit a similar interplay of

meaning-making resources to develop *explanations* of similar phenomena. To address this unexplored aspect, my investigation builds on the work by Gregorcic, Planinsic, et al. (2017). This is because I saw the topic of orbital motion explored by those authors as particularly apt for highlighting the distinction between *descriptive* and *explanatory* models in physics (as discussed in Etkina, Warren, & Gentile, 2006). Historically, Kepler’s laws constitute a *descriptive* model for the motion of planets around the Sun, while Newton’s laws of motion and his Law of Universal Gravitation provide an *explanatory* model of the same phenomenon (Holton & Brush, 2005). My desire with Paper III was to investigate how students’ non-disciplinary meaning-making resembles the latter, insofar as the students came to not only describe *what* happens, but also explain *why* it happens the way it does.

To this end, I present a final case study of two students (from the third data set) as they explore a feature of orbital motion with the PhET simulation software, *My Solar System* (PhET, 2018), on an IWB. I show that the students incorporate their bodily experience and enact a metaphor – namely, a two person dance which resembles the spinning dance done by Jack and Rose in *Titanic* (Cameron, 1997) – in order to communicate and reason mechanistically about the dynamics of a binary star system. For this thesis, I take mechanistic reasoning to mean reasoning that involves explanations of phenomena in terms of cause and effect mechanisms – that is reasoning about *why* and *how* (see Russ, Scherr, Hammer, & Mikeska, 2008 for an in-depth discussion of the topic). I show how the pair of students address a question by utilizing a diverse set of embodied, interpersonal, and largely non-disciplinary meaning-making resources, yet do so in a manner which fruitfully relates to a disciplinary treatment of the topic.

For the analyses of Paper III, I make use of a combination of two theoretical perspectives, both of which have been shown on their own to be useful ways of viewing meaning-making. The first, social semiotics, examines how meaning-making resources – such as the conversational resources of talk, gesture, touch, and body position, but also the (typically) disciplinary resources of mathematical equations and canonical physical laws – combine to afford various meaning potentials in social contexts. The second, embodied cognition, is interested in how thinking can be interpreted as an act of metaphorically-directed construction from elementary, experientially-gleaned cognitive building blocks. The details of these perspectives are presented in Section 2.4. In what follows, I review how the data were selected, how transcription was carried out, the topics of orbital motion and the orbital periods of binary stars, the detail of the analytic model used, and the analysis itself.

5.3.1 Selection of data ^{III}

For the purposes of Paper III, I chose to focus on a 2.5-minute section of video data from the third data set. This chunk of data involves a particular pair of

participants, whom I refer to as Adam and Beth.⁶⁴ The chosen 2.5-minute section of video data occurred approximately an hour and a half into the overall session (which lasted roughly three hours long), while Adam and Beth were exploring orbits with *My Solar System*. In the course of the session, the participants had already spent approximately 45 minutes exploring orbits in *Algodoo* as well as approximately 30 minutes with the *My Solar System* simulation. This pair of participants and, more specifically, this clip of video data was selected because the research team noticed that it includes a unique interaction between the participants, the likes of which we had not seen reported in a PER context. Unprompted to do so by the researcher in the room, Adam and Beth spontaneously engaged in an enacted analogy as a means of communicating and mechanistically reasoning about aspects of binary star dynamics. The enacted analogy was identified as a rich example of embodiment in physics which warranted a new kind of analytic attention.

5.3.2 Transcription^{III}

As I did with Paper I and II, for the presentation and analysis of the data in Paper III (Section 5.3.4), I use portions of transcript – translated by the research team from the students’ native Swedish⁶⁵ – as well as illustrations drawn from frames of the video data. Each line of the transcript is numbered (continuing the numbers from Section 5.2, for clarity) and labelled with the student’s pseudonym who spoke or acted out the content of the line. The transcript comprises the students’ speech (written in plain or underlined text) and/or non-verbal actions (written in [bracketed, italicized] text). In order to convey the coincidence of some of the verbal and non-verbal communicative actions, I underline the portions of the lines which coincided with a particular action and then describe the coincident action in the brackets immediately following the underlined text. For example, the line “Mhm, yeah. I agree. [nods her head]” would be used to refer to an instance where the speaker nodded her head while saying “I agree,” but did not nod during “Mhm, yeah.” Alternatively, in order to convey speech and actions which occurred consecutively, I omit an underline in the transcript. Thus, “Mhm, yeah. I agree. [gives a thumbs-up to Adam]” would be used to refer to an instance where the speaker first spoke the words “Mhm, yeah. I agree” and then gave a thumbs-up to Adam after she finished speaking. A full version of this transcript – in a style typical of conversation analysis – is included in Appendix E.

⁶⁴ Pseudonyms adopted from Rådahl (2017).

⁶⁵ The original analysis of this exchange was done with in Swedish and the points made throughout the English analysis were checked to be consistent with the Swedish version as well. For a detailed transcript of Adam and Beth’s interaction (with the Swedish and English side-by-side), see Appendix E. This transcript was included with Paper III as ‘supplementary data.’

5.3.3 Orbital motion ^{III}

As discussed by Gregorcic, Planinsic, et al. (2017), the topic of orbital motion receives only nominal attention in most upper-secondary physics programs, where students may be expected to simply know Kepler's Laws by name and formulation, for example. This surface level treatment of orbital motion might be due, in part, to the fact that celestial phenomena take place on spatial and temporal scales far removed from those of humans in everyday contexts. Additionally, a rigorous mathematical treatment, which might provide another avenue for students to engage with orbital motion other than their intuitions, is likely to be beyond the skill level of upper-secondary (and even introductory university) physics students. Dynamic computer visualizations – which can display how the positions of celestial bodies evolve with respect to time – have offered some ways for teachers to make orbital motion more visually accessible to students, but the students merely watching such visualizations are likely to remain relatively passive.

Alternatively, user-friendly simulation software can provide environments in which the topic of orbital motion can be approached with an emphasis on student-inquiry. Software such as the *My Solar System* simulation from PhET (PhET, 2018) and the open-ended digital environment of *Algodo*, especially when combined with collaborative interfaces such as an interactive whiteboard (IWB) (Gregorcic, 2015a), provide small groups of students with the opportunity to explore orbital motion and Kepler's Laws for themselves (Gregorcic, 2015a; Gregorcic, Etkina, & Planinsic, 2018; Gregorcic, Planinsic, et al., 2017; Rådahl, 2017). Students who are encouraged to explore orbital motion with these digital learning environments have been shown to spontaneously engage with the topic in ways which mirror science-like exploration (Gregorcic, Planinsic, et al., 2017).⁶⁶ In this spirit, Gregorcic and Haglund (2018) have used the interpretive lens of conceptual blending to theorize how the combination of simulation software and IWB allows students to compress celestial phenomena to the human spatial and temporal scales, thereby making it possible for students to explore and experience orbital phenomena in a 'hands-on' fashion.

5.3.4 The orbital periods of binary stars ^{III}

In this paper, I study the 2.5-minute portion of Adam and Beth's video-recorded conversation which precedes, comprises, and follows the Titanic-like dance. By way of a preamble to my analysis, I first examine the physics topic that the two students discussed from a disciplinary perspective, and in doing so, further clarify the analytic lens through which I have chosen to analyze

⁶⁶ For a discussion of how to incorporate instructional technology into an educational treatment of orbital motion at the upper-secondary or introductory university level, see Gregorcic et al. (2017) and references therein.

Adam and Beth's interaction. For the duration of the selected video clip, Adam and Beth are exploring the reason why binary stars never begin to orbit 'out of phase' with one another – i.e. both stars complete their orbit in the same amount of time. Specifically, the students are discussing the following question, which I refer to throughout the remainder of this section as the orbital period (OP) question:

Why are the orbital periods of the two binary stars always the same as each other?

This question is first posed by Beth and it serves as both of the students' focus for the 2.5-minutes clip that I analyze in Section 5.3.5. However, before I analyze the ways in which Adam and Beth came to answer the OP question, I first examine the critical features of a disciplinary answer in order to establish a disciplinary reference point against which I can compare Adam and Beth's conversation. Ultimately, I interpret the extent to which each informal utterance made by the students seems to relate (via embodied imagery) to the formal concepts which would be used by physicists in answering the OP question.

Though the OP question might not be considered a common discussion topic for many physics or astronomy classes, in what follows, I model how a physicist might construct an answer if the OP question happened to surface.⁶⁷ First, I assert that binary stars make up a two-body system wherein both bodies interact via centrally-directed, reciprocal forces. These forces are described by the Newtonian Law of Universal Gravitation, being attractive and falling off with inverse square of the distance between the objects' centers (valid for spherically symmetric objects). In such a system, Newton's laws of motion can be used to find that both bodies move on elliptical orbits with a common focus at the center of mass of the system.

One can explain the equally-long orbital periods by solving the two-body problem analytically (which I do not do here for the sake of brevity). Since each body is accelerated only by the centrally-directed force exerted by the other body, and since the center of mass of the system is always located on a straight line drawn between the two bodies, each body must always be located directly across the center of mass from the other body (though at a changing distance for non-circular orbits). Thus, as one body passes through a single revolution on its elliptical orbit around the center of mass of the system, the other body will necessarily remain opposite it at every point of the orbit, thereby completing a single revolution simultaneously with the first.

However, the OP question, as it was posed by Beth, can be addressed without necessarily being familiar with the full analytical solution to the two-body problem. Some implications can be drawn directly from fundamental

⁶⁷ There are, certainly, many different ways that a physicist might choose to answer the OP question, ranging from entirely mathematical to predominantly conceptual. For the purposes of my analysis, I present a more basic conceptual answer, as the features of such an answer can be more readily compared to the informal interaction of the two students.

principles that I use to deal with the two-body problem. For example, the accelerations of the two bodies are related by Newton's 2nd law to the forces the bodies exert on each other. The accelerations of respective bodies are thus parallel to the net force experienced by each body (in this case the same as the force exerted by the other body), which are themselves related by Newton's 3rd law (equal in size and opposite in direction). Following from Newton's laws, the temporal evolution of the direction and size of respective accelerations will also be similar for both bodies. The respective accelerations therefore always face in exactly opposite directions – and in the case of differing masses, have different sizes – yet maintain a constant ratio of sizes and change simultaneously in direction and absolute size (due to changing distance between the bodies as per the Law of Universal Gravitation). In this way, it can be seen how a periodic change in one body's acceleration will necessarily mean the same period of change in acceleration for the other body, both in terms of direction, as well as size.

I now apply the above reasoning to the case at hand. If one of the two bodies were to have a different orbital period than the other, this would also entail a different temporal evolution of its acceleration. In the case of elliptical orbits, where each point of the orbit has a unique direction of acceleration, this is particularly clear. The proposal of different orbital periods for the two bodies thus violates Newton's laws of motion. As I will show in Section 5.3.4, the students' reasoning, while not formulated in physics disciplinary language, is remarkably similar to the one presented here.

Below, I propose a selection of disciplinary-relevant aspects (DRAs; Fredlund, Airey, et al., 2015; 2015a) that will allow me to compare some of the aspects of a disciplinary analysis of the OP question with Adam and Beth's reasoning. Fundamentally, a disciplinary conceptual treatment begins with an appreciation that the stars' motion can be accounted for by Newtonian mechanics. Thus, a qualitative answer to the OP question in the given context might be seen as incorporating Newton's Third Law, Newton's Second Law, and Newton's Law of Gravitation by way of four DRAs:

- DRA₁: the orbital phenomenon of the binary system involves the interaction of two bodies,
- DRA₂: the two bodies are interacting reciprocally with one another,
- DRA₃: the interaction of the bodies with one another is what determines their motion,
- DRA₄: the interaction is attractive in nature.

These four DRAs can be seen as specific facets of the three Newton's laws mentioned above, phrased in a qualitative manner which accompanies the OP question. As summarized in right half of Figure 21 on the next page, DRA₁ and DRA₂ can be seen as facets of Newton's Third Law, DRA₃ as a facet of Newton's Second Law, and DRA₄ as a facet of Newton's Law of Gravitation.

These four DRAs outlined above constitute a conceptual treatment of the OP question as aligned with the discipline of physics.

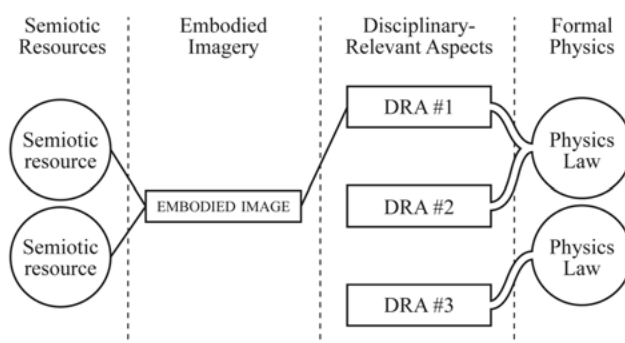


Figure 21. A diagram of the analytic approach used in this paper. My approach entails that I first observe the semiotic resources used by students (leftmost column) and interpret these resources in terms of the embodied imagery which they seem to imply (center-left column). I then compare this embodied imagery to disciplinary-relevant aspects (DRAs, center-right column). The DRAs are seen to be facets of the disciplinary physics laws (rightmost column) used in a formal treatment of the task at hand.

5.3.4 Analytic model ^{III}

In the following section, I analyze Adam and Beth's conversation by breaking down their multimodal utterances (moment-to-moment) into constituent semiotic resources (diagrammatically shown in the leftmost column, Figure 21, as aligned with the practices of conversation analysis). I then interpret the embodied imagery associated with each of these utterances (as discussed in Section 2.4.5) based on both the involvement of embodied semiotic resources and also the metaphorical structure of the resources in relation to one another (middle left column, Figure 21, as aligned with the perspective of embodied cognition). Since I am interested in the degree to which the students' non-disciplinary communication relates to DRAs, I then examine how the interpreted embodied imagery could be seen as relating to a set of DRAs identified from a disciplinary treatment of the task at hand (middle right column, Figure 21, as aligned with the perspective of social semiotics). The DRAs identified in our analysis are seen as facets of formal physics laws (rightmost column, Figure 21), such as Newton's Third Law, and constitute the relatively fixed semiotic patterns that make up the discipline of physics. In this way, I compare the students' dynamic, negotiated, and non-disciplinary meaning-making on the one hand (left half of Figure 21) with the more fixed system of disciplinary physics on the other (right half of Figure 21).

To illustrate the analytic approach further, I use an example from my study. In the two-person, *Titanic*-esque dance, the two students can be observed

holding hands and leaning outward from each other (ostensibly, imagining to spin around). In performing this action, the students are employing the semiotic resources of body position and haptic-touch. Thus, if I place the students' interaction in a diagram like Figure 21, these two semiotic resources occupy the leftmost column (see Figure 22). Next, while I temporarily defer what I acknowledge is a crucial explanation for the sake of illustrating my framework, I posit that these two semiotic resources combine to invoke an embodied image of ROTATING IN A PARTNER DANCE (middle-left column, Figure 22). The ROTATING IN A PARTNER DANCE image is a multifaceted one and likely the largest chunk of the mental elements which I identify under the category of 'embodied imagery.' Even in the initial posing of the dance when the two students simply hold hands and lean outward from each other, it is apparent that the rotating in a partner dance image necessarily requires two people pulling on each other symmetrically to spin around. Thus, simply by virtue of its material characteristics as a physical act of the two students, the dance can be seen as relating to *all four* DRAs for the question at hand (Figure 22). Eventually, as shown in the following analysis, the students elaborate on the ROTATING IN A PARTNER DANCE image via other semiotic resources in order to highlight the relevance of specific aspects which I see as relating to particular DRAs.

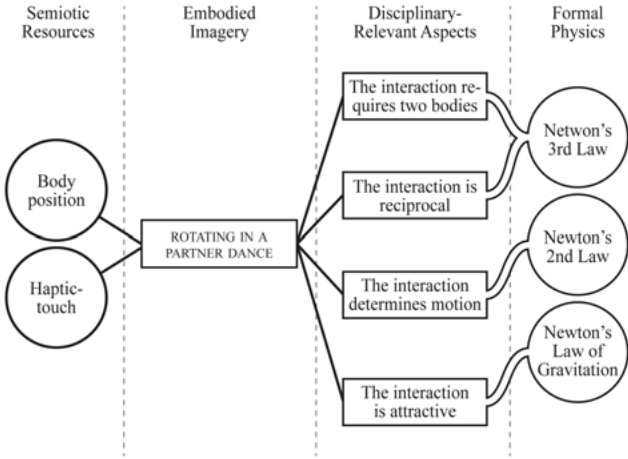


Figure 22. A diagrammatic representation of our analysis applied to the titular example of embodiment in this paper: the dance. I identify the semiotic resources of body position and haptic-touch (left column) as invoking the embodied image of ROTATING IN A PARTNER DANCE (middle-left column). This embodied image can be seen as relating to all four disciplinary relevant aspects (DRAs, middle right column) of the OP question, which in turn are aspects of three formal physics laws (right column).

Thus, as I analyze Adam and Beth’s interaction in the section that follows, I examine the informal semiotic resources the pair uses while reasoning about the OP question in relation to these four DRAs. Specifically, I interpret the semiotic resources used by Adam and Beth (such as talk, gesture, haptic-touch, and body position) as implying embodied imagery and then compare this embodied imagery to the DRAs identified above. In this way, I make visible the ways in which the students’ informal communication appears to match the character of more formal physics.

5.3.4 Analysis and discussion ^{III}

Segment 1: Before the dance

The first segment of data begins as Adam and Beth start to explore the motion of binary stars. In the time leading up to the first lines of the transcript, Adam and Beth select the “Binary star, planet” preset within *My Solar System* (as is shown in Figure 5 of Chapter 3), which involves two larger (star-like) bodies and one smaller (planet-like) body. The students allow the simulation to run for a few seconds, but upon seeing how complicated the motion of the three bodies is, Beth decides to construct a simpler binary star setup of her own by choosing the “Sun and planet” preset (Figure 23) and then setting the masses of the two bodies equal to one another.

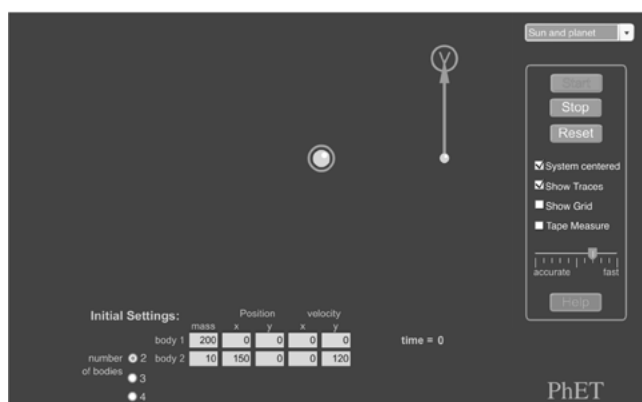


Figure 23. A screenshot of the *My Solar System* simulation showing the “Sun and planet” preset.

As the pair of students begin to explore this new binary star system on the IWB, Beth is surprised to see that both stars take the same amount of time to complete a single revolution in their respective orbits, especially while she changes the mass of one of the stars such that they are unequal again. Though it takes her many tries to explain her surprise in the right words, Beth eventually says to Adam, “but they are still the same [as each other]. The orbital

period[s are] the same. They have different orbits but will still get the same orbital period.” After the two students change the masses of the stars one last time Beth asks,

- 82 Beth Why does it happen like that? [*watching the IWB*]
 83 Adam Because it’s for only two planets, so it’s— [*points index fingers upward, Figure 24a*] I mean, you must always have a counterforce toward where the other planet is.
 84 Beth Yeah. [*looks at IWB*]
 85 Adam And if it changes faster... well then, I mean, the count— then there won’t be created any counterforce. [*follows the small, circular shape of the more massive star’s orbit with his index finger on the IWB, Figure 24b, left; then, looks back to Beth, Figure 24b, right*]

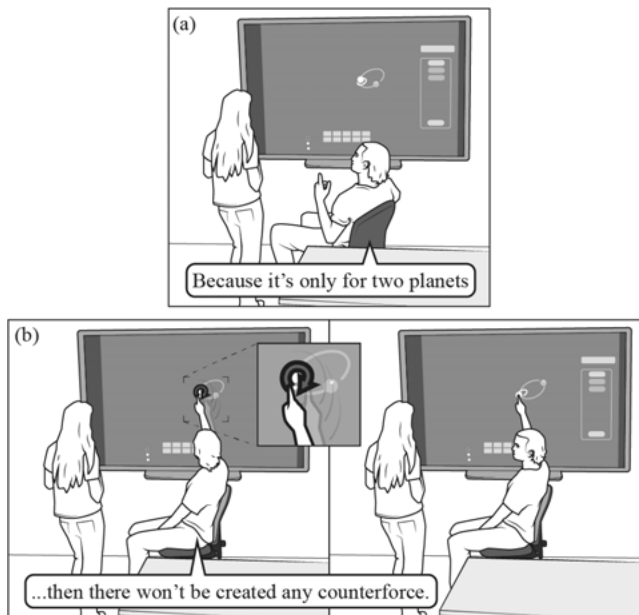


Figure 24. Illustrations of Adam’s multimodal utterances in (a) line 83 – where we see him including an embodied image of a RECIPROCITY OF INTERACTION – and (b) line 84 – where he can be seen involving an embodied image of FORCED AROUND.

I first want to flag the way that Beth originally formulates the OP question, as it becomes relevant for tracking the progress of the students’ interaction. When Beth asks the question ‘why does it happen like that?’ in line 82, I take

it that she is inquiring into why the *system* of two stars behaves as it does.⁶⁸ Though Beth specifically talks about the periods of each body in the time leading up to the OP question in line 82, she ends up using a phrasing which emphasizes the phenomenon as a whole. Given that the formal treatment of the OP question involves an appreciation of the reciprocity of interaction between *two* bodies, Beth's wording of the OP question suggests that she is considering the phenomenon in a manner which is 'too holistic.' Indeed, though I do not claim to know what Beth was thinking, if I examine the way she spoke about the orbiting stars in line 82 of the transcript, I assert that she does not clearly express an appreciation of any of the four concepts I highlighted in the formal treatment (Section 5.3.4).

In his first attempt to answer Beth's question, perhaps in response to how Beth had inquired about the behavior of the phenomenon *as a whole* in line 82, Adam chooses to emphasize that the binary system is made up of two distinct, interacting bodies. He centers his fingers symmetrically over his shoulders in a way which I take as referring to two discrete objects that are playing equivalent roles in a phenomenon. Together, his speech and gesture in the beginning of line 83 feature an embodied image of a SYMMETRIC PAIR. In comparing this part of his utterance to the DRAs for answering the OP question, this implied embodied image strongly resembles DRA₁, that *the interaction requires two bodies*.

Adam goes on in line 83 to say, "you must always have a counterforce toward where the other planet is." Here, his use of the word counterforce (translated from the Swedish, *motkraft*) is of particular interest, not least because it seems to be an example of Adam attempting to incorporate more formal vocabulary while answering Beth. On the one hand, a 'counterforce' grammatically counters *something*, namely another force. Thus, Adam's use of the word implies a RECIPROCITY OF INTERACTION between two bodies. Such an embodied image could be worthwhile in the discussion of the OP question, as it relates to DRA₂, that *the two bodies interact reciprocally with one another*. On the other hand, however – and despite my being able to see 'counterforce' as an expression of a RECIPROCITY OF INTERACTION – it is not clear what Adam means with the word while communicating with Beth. Thus, Adam's use of 'counterforce' is both a potential implication of a useful embodied image, and also a somewhat ambiguous term in the context of his conversation with Beth. In addition to using "counterforce," Adam indicates a directionality to the interaction of the stars in his use of the word "toward." By stating that "you must always have a counterforce toward where the other planet is," Adam implies an embodied image of ATTRACTION, as is used in

⁶⁸ Beth uses the third-person singular pronoun "det" (in English, 'it') as the subject of the question, which, due to the en/ett system for nouns in the Swedish language, excludes the possibility of her referring to a specific planet by itself.

Newton's Law of Gravitation and is captured in DRA₄, that *the interaction is attractive in nature*.

In line 85, Adam presents a counterfactual conditional statement, “and if it changes faster, [...] then there won't be created any counterforce.” Adam uses this counterfactual in his arguments several times over the course of his answering the OP question. The counterfactual seems to be that, if Star 1 were to orbit faster than Star 2 in a binary system, this would result in a lack of a “counterforce,” which Adam appears to find important in some way for explaining the stars' motion. Here in line 85, Adam does not present his counterfactual in a clear manner and it is only with the context of the following section that I (as a researcher) am able to interpret what he means. Adam uses vague wording such as “if it changes” and “be created any counterforce” without explaining *what* is changing or what it means to *create* a counterforce, or how it relates to the other star's motion.

Still, as the words of the counterfactual scenario co-occur with a circular gesture at the IWB, I infer that Adam is semantically linking his notion of counterforce (however ambiguous the term remains) with the orbital (circular) motion of one of the stars. This multimodal utterance relates to and implies an embodied image of FORCED AROUND since it involves an object being moved around in orbit by some force. Thus, this embodied image can be seen as resembling DRA₃, that *the interaction determines motion*.

It can be seen at the end of line 85 that Adam turns his gaze back to Beth as if to check how well his explanation is working. However, unlike in line 83 where she encourages Adam to continue, after line 85, Beth silently gazes at the IWB, offering no confirmation to Adam that she has followed his reasoning. Indeed, from her reaction and from the ambiguity of his utterances, I suggest that Adam's attempt to explain his answer to her question has not convinced Beth thus far. Nonetheless, while his utterances do not work in the context of the conversation, I am still able to interpret Adam's utterances as involving each of the four critical aspects used in answering the OP question. In the next segment, Adam tries to answer Beth's OP question again, this time using the dance to better convey the same formal concepts he has already begun to involve in lines 83 and 85.

Segment 2: The dance

When Beth does not respond to Adam's utterance in line 85, Adam chooses to involve his and Beth's bodies to act out his reasoning. It is at this time that the first instance of the dance occurs, which the students eventually enact twice.

- 86 Adam If you and I were to rotate around like this [*extends both hands to Beth, Figure 25a, left*]
87 Beth Mhm. [*grabs Adam's hands, Figure 25a, right*]

- 88 Adam Then I cannot start to rotate faster than you... [*pulls on Beth's hands, then rolls in his chair to the side of Beth while trying to pull in the direction of his original position, **Figure 25b***] even though you weigh less than me. [*points to Beth, then puts hands down*]

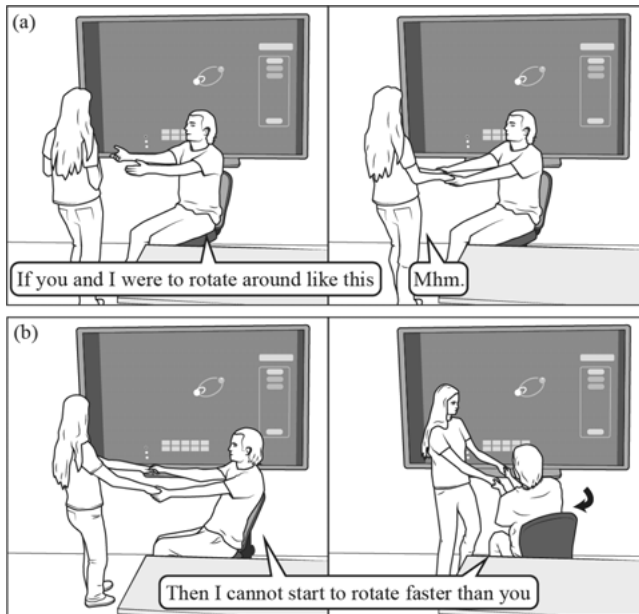


Figure 25. (a) Adam offers his hands to Beth with an invitation to “rotate around” (line 86). (b) Adam then acts out an unrealistic over-rotation in the dance context by scooting in his chair (line 88). This is the dance, which resembles the spinning that Jack and Rose do in *Titanic* and which I suggest implies an embodied imagery of *ROTATING IN A PARTNER DANCE*.

In lines 86 and 88, Adam involves Beth in a dance, which I see as a coordinated set of semiotic resources including haptic-touch and body position. Importantly, however, despite being composed of distinguishable resources, the dance seems to elicit a single, coherent embodied image: *ROTATING IN A PARTNER DANCE*. Unlike the sets of semiotic resources used by Adam in lines 83 and 85, the set of semiotic resources in the dance are coordinated as a single multimodal ensemble and connote a unitary image of embodied action. It is important to note here, that, while it may be unsurprising to the reader that acting out a dance in this situation might invoke *ROTATING IN A PARTNER DANCE* for the two students, I emphasize that it should not be taken for granted that coordinated sets of semiotic resources produce coherent embodied imagery. For example, compare the talk and gesture used by Adam in lines 83 and 85 with the haptic-touch and body position of the dance in lines 86 and 88

(leaving aside talk and gesture in this latter instance, for now). In the first instance, as I have argued, talk and gesture seem to coordinate in a manner that make *implicit* reference to embodied imagery. In the second instance, haptic-touch and body position of the dance coordinate in a manner that make *explicit* reference to an embodied image. Therefore, Adam coordinates semiotic resources in an effort to make multimodal meaning in both cases, but only in the latter do we see a robust, unambiguous embodied image. With the dance, Adam communicates with Beth via the participatory semiotic resources of haptic-touch and body position as part of a pattern of behavior, which seems to require no abstraction.

Now, in examining how rotating in a partner dance relates to the formal treatment of the OP question, this embodied imagery can be seen to have the potential of relating to all four DRAs: the dance is an activity where two people (DRA₁) pull (DRA₄) on one another (DRA₂) as a means of rotating around (DRA₃). In this way, ROTATING IN A PARTNER DANCE has an explanatory potential for answering the OP question in a manner that goes beyond the embodied imagery employed across lines 83 and 85 (before the dance).

Furthermore, in line 88 Adam talks and gestures *around* the dance in order to highlight particular aspects for Beth. Since the dance involves the powerful, embodied imagery of ROTATING IN A PARTNER DANCE through the coordination of haptic touch and body position, Adam is able to leverage other semiotic resources, namely talk and gesture. By doing so, he is able to comment on the dance as he answers the OP question. Line 88 shows him acting out the same counterfactual he introduced in line 85 by over-rotating his body position in the dance with respect to Beth and saying, “then I cannot rotate faster than you” (Figure 25b). Here, it seems that Adam is relying on Beth’s instincts about the dance – or more precisely her embodied intuitions about rotating in a partner dance – so that she will recognize that his improbable over-rotation in the dance analogically relates to the impossible ‘decoupling’ of the orbital periods in the binary star system. Adam also draws attention to how an over-rotation is unrealistic despite the difference in his and Beth’s masses. This is likely offered as an explanation for why Beth’s changing of the stars’ masses in *My Solar System* before the OP question did not result in the stars becoming ‘out of phase’ with one another. When he uses the additional semiotic resources of talk and gesture around the dance – along with a variation of his body position in relation to Beth⁶⁹ – in a re-presentation of the counterfactual from line 85, Adam is foregrounding the features of the dance which relate to DRA₃. This is an example of how, though the ROTATING IN A PARTNER DANCE image has the potential to relate to all the DRAs, specific attention can be

⁶⁹ Indeed, purposeful variation of semiotic resources seems to be a critical feature of Adam’s more successful utterances. An attention to Adam and Beth’s interaction from a Variation Theory perspective (Fredlund, 2015; Fredlund, Airey, et al., 2015) could offer some useful insights, but given the length of this manuscript already, I choose to leave it now as an open topic for future research (see Chapter 8).

drawn to DRA-specific features within the ROTATING IN A PARTNER DANCE image through the inclusion of other semiotic resources. As Adam finishes his thought, he pauses to let Beth reply.

- 89 Beth Because they are holding each other... [turns to look at the IWB and brings hands together, interlocking her fingers, **Figure 26, left**] in some way. [turns back to Adam and extends her hands toward him, **Figure 26, right**]

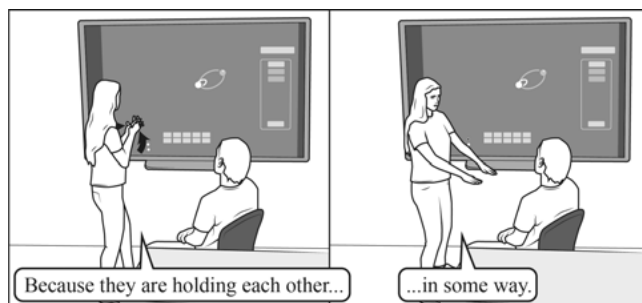


Figure 26. Beth demonstrates her interpretation of the relationship between the dance and the orbiting stars with two gestures indicating an embodied image of holding together (line 89).

In line 89, Beth tries to explicate the analogical relationship between the binary star system and the dance. She gestures to suggest ‘holding’ by bringing her hands together while looking at the IWB, then extends her hands while facing Adam in reference to the dance. She uses the pronoun “they” (*de* in Swedish) to indicate that she is referencing the stars, but combines this with a gesture that refers to the dance she just completed with Adam (Figure 26, right). Especially when compared to Beth’s utterance in line 82, her utterance in line 89 seems to involve something of a HOLDING TOGETHER embodied image. When compared to the DRAs used in our formal treatment, the holding together image shares a resemblance with DRA₁, DRA₂, and DRA₄.

While the attractive nature of the interaction between the stars is invoked multiple times in Adam and Beth’s interaction, it is, perhaps surprisingly, never elaborated on by the students in terms of gravity, the physical mechanism in the astronomical realm with which they were certainly familiar. I do note, however, that the activities preceding and following the excerpt presented here dealt with gravitational interactions quite explicitly, and both students expressed an appreciation of gravity as the mechanism of interaction between the involved celestial bodies. By saying that the stars are holding each other “in some way,” Beth presents a ripe opportunity where the students might have linked their discussion with more formal terminology. Yet, as is seen throughout the rest of the analysis of Adam and Beth’s interaction, this gravity thread is never teased out explicitly. Nonetheless, by her utterance in

line 89, I can suggest that the dance has made Beth more aware of the two-bodied, reciprocal, and (to a lesser degree) attractive nature of the binary star system. As if spurred on by Beth expressing part of the answer he is trying to convey, Adam invites her to engage in the dance again, this time while standing up.

- 90 Adam Exactly, because– I mean, because you– [*stands up, extends his arms, and grabs Beth’s hands again, **Figure 27a, left***] because we hold each other here. [*they lean outward from each other and stop with their arms fully extended, **Figure 27a, right***]
- 91 Beth Mhm. [*stays in position with Adam, both of them holding hands with their arms extended*]
- 92 Adam So even though I weigh more than you, then I will– I couldn’t start to rotate around here. [*while leaving his hands in place, steps around to the side of Beth again, **Figure 27b, left***] because then you just fall out that way. [*points to Beth, then puts hands down*] because then there is nothing holding you anymore. [*points away from Beth with the thumb of his right hand to the position in the dance across from her, **Figure 27b, right***]
- 93 Beth Yeaah. [*drops her hands and looks to the IWB*]

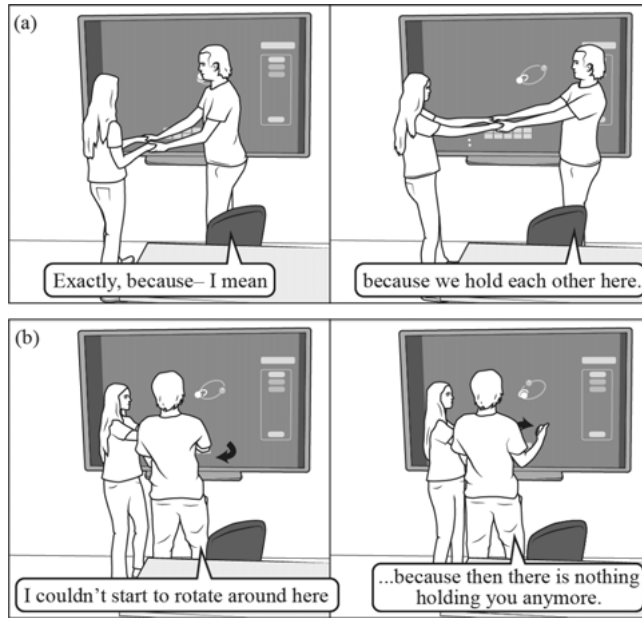


Figure 27. (a) Adam reengages in the dance with Beth from a standing position (line 90, left frame), this time making sure to draw Beth's attention to the outward position from where the two of them would be holding one another (line 90, right frame). (b) Adam over-rotates again (line 92, left frame). He then holds the over-rotated position and highlights that "there is nothing left to hold" Beth while gesturing to the space that he has left unoccupied (line 92, right frame).

As Adam leads Beth in the dance a second time, he makes sure to emphasize the normal body position that one would expect in such a dance (i.e. with both participants across from each other with arms extended). In doing so, Adam represents a more authentic version of the dance, pulls more on Beth's hands, and better establishes the spatial orientation he and Beth would inhabit if they were to actually rotate around. He then acts out the counterfactual scenario again (from lines 85 and 88) by over-rotating to a position to Beth's right. As in the first instance of the dance, Adam provides a commentary to the dancing action via talk and gesture. In this way, ROTATING IN A PARTNER DANCE seems to elicit Beth's embodied intuitions. Adam then highlights specific aspects he sees as relevant to the OP question. This time, he first gestures past Beth to indicate the way that she would "fall out" of the dance and then gestures to the space which he left behind by over-rotating where there is "nothing holding [Beth] anymore."

Interestingly, in this way, the dance can be seen as functioning as a coordinating hub (Fredlund et al., 2012; Volkwyn et al., 2018) for Adam and Beth's interaction. The dance elicits a robust, shared embodied image around which the semiotic resources of talk and gesture are used to negotiate and highlight

meanings. However, while PER studies into the roles of semiotic resources have emphasized the importance of *persistent* representations (Fredlund, Airey, et al., 2015; Kress, 2010) in the role of coordinating other semiotic resources, I show my examination of Adam and Beth's interaction that students can coordinate their meaning making around a non-persistent, experientially-shared embodied image.

After the second dance in lines 90 through 92, Beth responds with a satisfactory "Yeaah" (line 93), as if to indicate that she has finally arrived at an explanation to her OP question which intuitively makes sense. The discussion of binary stars continues through a third and final segment of her and Adam's interaction, wherein she expresses her rationale more explicitly.

Segment 3: A further question

The third segment of the data begins with an interjection from the researcher (in this case, Rådahl was the researcher present), who, after watching the interaction of Adam and Beth with the dance, and in response to their exchange, pushes the two students to strengthen the analogical connection between the dance and the orbiting stars. This is done with the following question: *In [the dancing] situation, you are pulling on one another with forces; if you try to imagine force vectors or forces on the objects, how will they be directed and can you see any similarities with—?* As the researcher refers to the dance, he extends his arms outward as the students did in the dance. Then, when he refers to the "objects", he points to the stars on the IWB from his seat at the back of the room. Before the researcher can finish the question, Adam answers.

- 94 Adam I mean, they are directed toward each other [*holds hands up to the IWB and follows both stars as they orbit, pointing his pinky fingers toward each other, Figure 28, left*] all the time. [*repeats the motion with his index fingers*]
- 95 Beth No, here they are directed away from each other. [*steps up to the IWB so that Adam has to move and holds her hands over the apocenters of the orbits, pointing her index fingers out from the center, Figure 28, right*]

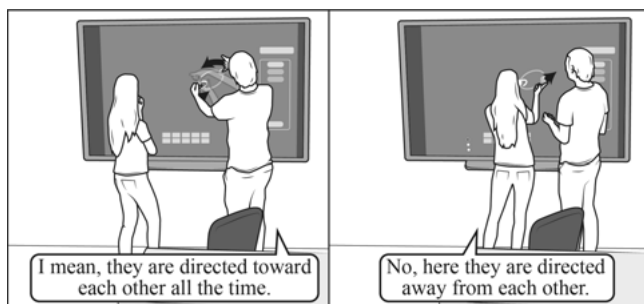


Figure 28. Adam answers the researchers' question by pointing his fingers inward toward each other as he traces the motion of each star on the IWB (line 94, left frame) – involving the embodied imagery of SYMMETRIC PAIR and ATTRACTION. Beth disagrees and points outward from the center of mass at the apocenters of the orbits (line 95, right frame) – involving the embodied imagery of SYMMETRIC PAIR and REPULSION.

While Adam responds to the researcher's question correctly, indicating central, inward-directed forces on the IWB (line 94) Beth incorrectly describes the forces as directed "away from each other" (line 95). She answers in a manner consistent with a common perception of an outward force in rotational motion. However, her answer here also highlights one of the possible drawbacks of using the dance as an analogy for the binary star system: by involving her embodied intuitions from a system where she takes on the role of one of the orbiting bodies, she is likely to involve her intuitions which stem from experiencing the non-inertial reference frame. During the dance there is an *apparent* outward force experienced by the dancers from rotation. To make things worse, when Adam and Beth lean outward from each other in the dance (Figure 27a, right), there is a very real (not imagined) torque caused by Earth's gravity which pulls the dancers apart. Worse still, the force felt by Adam and Beth in their hands *increases* as they lean further away from each other. Thus, it can be seen here that the intuitions that accompany the enacted analogy of the dance could be reasonably expected to lead Beth to incorrect conclusions with regards to the binary star system.

Despite the difference in their answers, however, both Adam and Beth gesture with both hands in a radially symmetric manner. The students' expressions suggest an embodied image of a SYMMETRIC PAIR (as in line 82), which in turn aligns well with both DRA_1 and DRA_2 . Adam combines the symmetric pair image with an image of ATTRACTION in a manner which aligns with DRA_4 . Conversely, Beth combines the symmetric pair image with an image of REPULSION.

- 96 Adam No.
- 97 Beth No? [*steps back from the IWB*]
- 98 Adam Because you can see... [*waits for the stars to orbit until they are nearest each other, then pauses the simulation*] See, now they are directed like so. [*holds his hands over the two stars in the simulation and points his fingers inward, **Figure 29a, left***] That is why they go— go around— *inaudible* [*looks at Beth and traces a small circle with his hands on the IWB, **Figure 29a, right***]
- 99 Beth Yeaaaah. And then they are directed toward each other, so yeah. [*steps up to the IWB and traces the shapes of the orbits while pointing her index fingers toward each other, **Figure 29b**; then Adam presses play*]

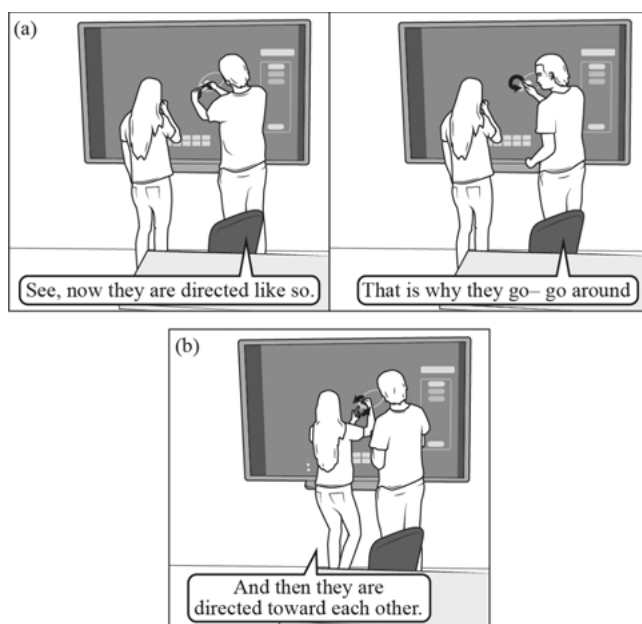


Figure 29. (a) Adam points his fingers toward each other over the stars on the IWB to show the inward direction of the forces (line 98, left frame). He then gestures in a circular motion while explaining that this is what keeps the stars going “around each other” (line 98, right frame) – which I interpret as involving the embodied image of *FORCED AROUND*. (b) Beth demonstrates her understanding of Adam’s explanation by mirroring his inward pointing gesture against the IWB (line 99). In doing so, she involves the embodied image of *ATTRACTION* alongside the image of a *SYMMETRIC PAIR*.

Though Adam does not explicitly make a connection between the stars on the IWB and the dance, he chooses to pause the simulation at a moment where his inward-pointing fingers most closely resemble the arrangement of two participants’ arms during the dance. That is, with the two stars near one another in the simulation, Adam is able to position his fingertips together in a manner

which resembles his and Beth's hands moments before. Again, Adam involves the embodied imagery of a SYMMETRIC PAIR along with an image of ATTRACTION. Furthermore, as he explains to Beth that the inward direction of the forces is what causes the stars to "go around" while gesturing in a circle on the IWB (line 98), Adam seems to make a connection between the attractive nature of the forces acting on the stars and the overlapping of the orbits traced out by the software. By involving an embodied image which I label again as FORCED AROUND, Adam is once again relating to DRA_3 . Perhaps surprisingly, the students once again refrain from stating the formal reason that these forces are attractive between the stars (i.e. that the forces are gravitational). Rather, Adam refers informally to the inward direction of forces via the FORCED AROUND embodied image. While it remains untested whether or not bringing up gravity more explicitly would have helped Beth make sense of the binary star dynamics, it seems likely to me that grounding parts of the interaction such as this in familiar formal terminology could have helped cue more explicit and correct reasoning (see Rådahl's (2017, p. 31) discussion of possible teacher interventions).

In line 99, Beth makes an utterance of her own which involves the symmetric pair image with image of attraction. Adam presses the play button on the simulation and, in the next line, follows the stars around on the screen with his fingers pointed inward.

- 100 Adam So here they are directed toward each other [*follows the stars as they orbit in the simulation with his fingers pointed toward each other, again, as Beth watches*]
- 101 Beth Toward each other. Okay.
- 102 Adam So... then their forces [*points his fingers together in air, Figure 30a, left*] can be represented [*extends his hands toward Beth, Figure 30a, right*] as our hands, kinda.
- 103 Beth Mm.
- 104 Adam So, for the two of us to be able to rotate around [*points a finger upward in the air and twirls it around in circles while looking at Beth*] you have to lean out more than I have to. [*points toward Beth, then brings his hands toward his chest to emphasize himself*]
- 105 Beth I must have a larger orbit! [*steps toward the IWB and traces the shape of the larger orbit in the simulation with her index finger while looking at Adam, Figure 30b*]
- 106 Adam Exactly.
- 107 Beth Nice!

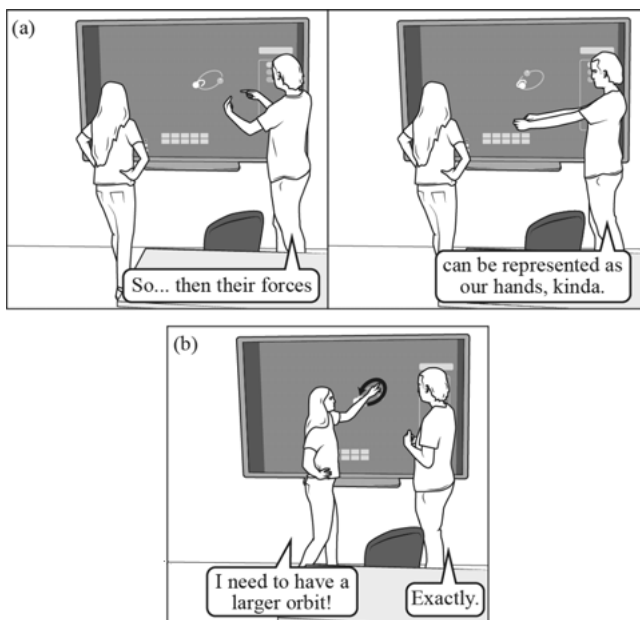


Figure 30. (a) Adam explicitly links the pointing gesture for the forces of the binary star system (line 102, left frame) with his and Beth's arms during the dance (line 102, right frame) – verbally and gesturally involving *ROTATING IN A PARTNER DANCE*. (b) Beth gestures along the larger orbit on the IWB while saying that she needs to have a “larger orbit” (line 105), which seems to imply an embodied image of *LIGHTER IS FARTHER*.

In this last section of transcript, Adam finally makes an explicit link between the orbiting stars on the IWB and the dance. He holds his hands out to Beth in a gestural reference to the dance via talk, similar to how Beth did in line 8, going on to explain that, in the dance, Beth would lean out more than him since he weighs more than her. Thus, Adam is able to elicit the imagery of *ROTATING IN A PARTNER DANCE*, this time in a non-enacted fashion, as he and Beth have already co-enacted the dance, and thus, shared some common ground (Roth & Lawless, 2002a). Leveraging his mutual experience of the dance with Beth, Adam emphasizes a feature of the dancing which helps to cement the link between the dance and the binary system on the IWB. Adam makes use of the intuitive understanding he and Beth have about how the dance works, in particular, how the experience is different for partners of different mass. Here the embodied imagery of *ROTATING IN A PARTNER DANCE* seems to be related, in a slightly different manner than before, to Newton's Second Law and *DRA*₃.

In response to Adam, Beth steps up to the board, traces her finger around the larger orbit (of the less massive star), and excitedly states that she “must have a larger orbit” (Figure, 30b, line 105). She chooses words which put her

in the role of the star grammatically, suggesting a strong conceptual intermingling of the experiential realm of the dance and astronomical realm of the binary stars.⁷⁰ Similar grammatical use of the first-person pronoun to identify with an external phenomena has been documented in the language of expert physicists (Ochs, Gonzales, & Jacoby, 1996), which suggests that, to a degree, Beth's utterance can be seen as containing elements of disciplinary discourse. In this way, and for the first time over the course of the entire 2.5-minute interaction, Beth offers an utterance which suggests an appreciation of why changes in the mass of a star will affect the *size* of the orbit, but will not make its orbital period fall 'out of phase' with that of the other star. She seems to involve an embodied image of LIGHTER IS FARTHER (which might be the closest of all our identified embodied imagery to a p-prim or image schema, i.e. the 'smallest' image) and, like Adam in the line before, this imagery seems to relate well to Newton's Second Law and DRA₃.

At this point of Adam and Beth's interaction, I choose to end the analysis. The two students do continue on after this exchange, but since they are largely satisfied with their discussion and the manner in which they have addressed the OP question, they continue on to explore other features of the *My Solar System* simulation and other orbital motion situations. As the analysis of the three segments above comprises a lengthy, finer-grained breakdown of the 2.5-minute interaction, I now attempt to 'zoom out' and summarize the findings in order to address some of the larger-grained features of Adam and Beth's conversation. I include Figure 31, a table-like diagram which comprises the semiotic resources, embodied imagery, and DRAs associated with each line of Adam and Beth's conversation for all three segments of video data analyzed above.

⁷⁰ I acknowledge that an analysis which involves conceptual blending (Fauconnier & Turner, 1998) could be undoubtedly applied to Adam and Beth's interaction. Nonetheless, with my interest in how Adam and Beth used their bodies to make meaning about astronomy, I prefer to focus on the insights gained from a perspective informed by embodied cognition and social semiotics.

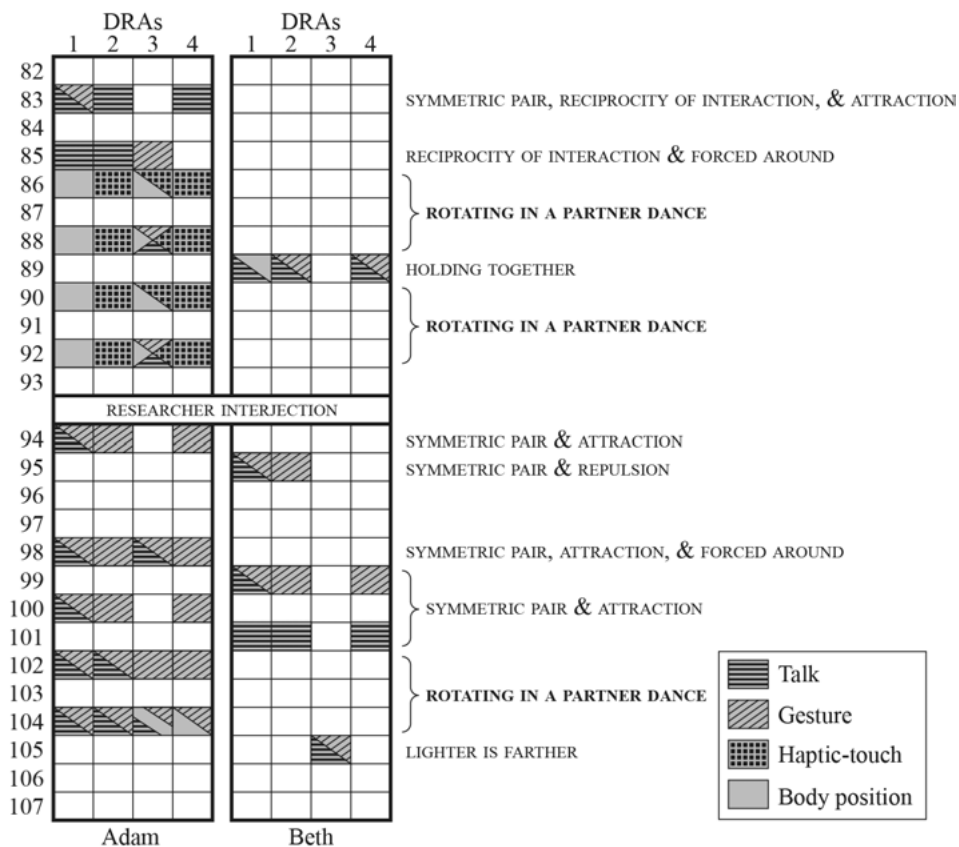


Figure 31. A line-by-line summary of Adam and Beth's interaction. Each row corresponds to a line of dialogue and each column corresponds to one of the four disciplinary-relevant aspects from the formal treatment of the OP question (*recall*, DRA_1 states that the interaction requires two bodies, DRA_2 states that the interaction is reciprocal, DRA_3 states that the interaction determines motion, and DRA_4 states that the interaction is attractive). I pattern each cell with the type of semiotic resource utilized by Adam or Beth within that line that I interpret as relating to that disciplinary-relevant aspect. The embodied imagery corresponding to each line is listed to the right.

In Figure 31, one of the first things to note is the progressive incidences of DRAs in Beth's utterances. When she initially asks the OP question at the start of our data, Beth might have been thinking about the complex binary star system in a too holistic way. However, over the course of the entire 2.5-minute interaction, she can be seen as producing utterances which collectively express all of the four disciplinary-relevant aspects (admittedly, never involving all

four DRAs within a single utterance⁷¹). First in line 89 (Figure 26), I interpret Beth's utterances as implying DRA₁, DRA₂, and DRA₄, since she mentions the two stars "holding each other" and gestures to the IWB suggesting an image of holding together. The researcher interjects between line 93 and 94 and the students are explicitly directed to consider the direction of the interaction between the two stars. Following the researcher's question, Beth's utterances imply DRA₁, DRA₂, and DRA₄ again as she gestures against the IWB with an image of a symmetric pair and attraction (line 99, Figure 29). Finally, as Beth relates her smaller size to the less massive star in the simulation (line 105, Figure 30), I interpret her utterance in as implying the last of the DRAs, DRA₃, as she talks and gestures at the IWB with an image of lighter is farther.

This helps me evaluate the worthwhileness of Adam and Beth's informal, disciplinarily-unconventional interaction. While it is clear that Adam was, from the beginning, at least implicitly involving all the necessary features (DRAs) for answering the OP question as aligned with the discipline, it can also be seen how Beth comes to express all of the same features for herself as some evidence of learning. By interpreting the two students' utterances in terms of the implied (and occasionally enacted) embodied imagery, I can value the details of the conversation as fruitful exploration even from a disciplinary perspective.

Another aspect of Adam and Beth's interaction made apparent by Figure 31 is the evident multiplicity of the semiotic resources within each cell (i.e. the number of semiotic resources used within each line which I see as relating to each DRA). While talk and gesture are frequently used in combination by both Adam and Beth, the 'densest' cells are those associated with the dance in lines 88, 92, and 104. Each of these lines include instances of Adam elaborating on the embodied imagery of ROTATING IN A PARTNER DANCE – via a simultaneous layering of three or four of the semiotic resources – to highlight aspects of the dance which I see as related to DRA₃. While the multimodal transcript presented throughout this section provides a necessary level of detail to motivate our interpretations of Adam and Beth's interactions, I see that summative tables of student interactions like Figure 31 could be academically useful in future research for recognizing patterns in students' use of semiotic resources and/or evocation of embodied imagery.

⁷¹ It, perhaps, should not be surprising that Beth never implies all four disciplinary-relevant aspects in a single utterance, since Adam consistently provides her with utterances that *do* include all four disciplinary-relevant aspects and she tends to simply agree with him when he seems to be making sense.

5.3.5 Synthesis and discussion ^{III}

Pushing theory forward

Through my reflection on how Adam and Beth utilized non-disciplinary semiotic resources to reason mechanistically about binary stars, I see my analysis in from Paper III as contributing to theoretical considerations within PER. The first of these involves the combination of social semiotics and embodied cognition into a single analytic framework (which I discuss in response to Research Question 2 in Section 6.4). The other two theoretical contributions center on how I am able to (1) provide evidence for non-persistent hubs around which semiotic resources can be coordinated and (2) suggest a further nuancing of the distinction between embodied learning activities (ELAs) and kinesthetic learning activities (KLAs). Both of these topics are discussed below.

Embodied imagery as coordinating hubs

Fredlund et al. (Fredlund, 2015; Fredlund et al., 2012) and Volkwyn et al. (2019, 2018) have studied how a persistent semiotic resource (such as a diagram or a large red arrow) can serve as a hub for coordinating other non-persistent resources. In my study, I see examples of this type of coordination when the students use the content on the IWB screen as a backdrop for gestures. For example, the running simulation in line 94 and the paused simulation in line 98 serve as a persistent representation against which gestures representing forces were layered – akin, also, to what was reported by Gregorcic, Planinsic, et al. (2017). However, it can also be seen that, with the dance, Adam is able to coordinate talk and gesture around the embodied image of his and Beth’s previous body positions even when they are no longer physically standing in those places. In this way, the image of the dance seems to *persist enough* for Adam and Beth – even if the persistence is only mental – for the two of them to make meaning around it, similar to how students can make more complex meanings around a persistent ray diagram (Fredlund et al., 2012) or a persistent cut-out paper arrow (Volkwyn et al., 2018). Thus, with the insights gained from this case study, I might propose an expansion to the social semiotic theory in the context of PER: in students’ process of meaning making, a good candidate as a hub for the coordination of semiotic resources is a shared embodied image, which ‘persists’ either physically or figuratively enough to be spoken and gestured around intelligibly. Future research could explore how gestures and body position can demarcate the environment to form semipersistent resources for the anchoring and coordination of non-persistent semiotic resources. Examples of such demarcation may be found in non-disciplinary resources – i.e. the locally agreed-upon signs used in Energy Theater (Scherr et al., 2013) (e.g. ‘jazz hands’ for thermal energy) – as well as in conventionalized signs in formal discourse of physics – i.e. the right-hand rule.

ELAs and KLAs

The analysis of this case also provides a more nuanced conception of the ways that students' bodies might be incorporated into the learning of physics. Specifically, while Scherr et al. (2012) have suggested categorizing physically-active learning activities as either embodied (ELAs) or kinesthetic (KLAs) (as discussed in Section 2.4.6), I see the interaction of Adam and Beth as involving features of both categories. Similar to an ELA such as Energy Theater (Daane, Wells, & Scherr, 2014; Scherr et al., 2013; Scherr, Close, Close, et al., 2012; Scherr, Close, McKagan, et al., 2012), the two students in this case study take on the roles of physical bodies in order to metaphorically act out how they behave; however, similar to how Scherr et al. (2012) define a KLA – and as is showcased with the *energy-flow-resistance* lesson described by Bruun et al. (2016) – I see the students (particularly Beth) using their bodies as sensors for physical forces and interpreting the sensation of these forces to formulate understandings of physical phenomena on a conceptual level.

This leads me to propose a more general characterization of ELAs as a process of *embodying* abstract ideas within students' physical bodies and, conversely, KLAs as a process of *abstracting* inputs from students' physical bodies into more formal conceptions. With such a perspective, the case I present in Paper III seems to involve both of these processes simultaneously and continuously. Perhaps, then, effective instances of students learning which involve their bodies necessarily demand both of these ELA/KLA processes in iterative loops. For the interested researcher, my analysis presents an example of embodied learning which seems to subvert an exact placement in either of the ELA or KLA categories exclusively, giving me reason to speculate on how labels of activity such as these might apply to a finer grain size, moment-to-moment account students' embodied interactions. I suggest that, in many of the cases labelled as either KLAs and ELAs, students might actually be continually switching how they use their bodies between 'body-as-a-role-player' and 'body-as-sensor' in iterative loops as they leverage their bodily intuitions to both *embody the abstract*, as well as *abstract from the body*.

Implications for teaching

The activity in which Adam and Beth participated during this study was framed by the digital tools in the environment and prompts given by the researcher. As discussed in Sec. III, the *My Solar System* simulation in combination with the IWB effectively shrinks celestial phenomena to human scale (spatially and temporally) (Gregorcic & Haglund, 2018). Other studies have shown how such a technological combination elicits a degree of embodied engagement from students (Gregorcic, 2016; Gregorcic et al., 2018; Gregorcic, Planinsic, et al., 2017). Beyond this, the activity was epistemologically framed (Bing & Redish, 2009) as an exploratory, playful activity (both through the open-ended prompt and also, perhaps by the nature of the

simulation software itself, as discussed in Paper II). Taking the overlap of these two framings (technological and epistemological), I suggest that the activity was set up in a manner which encouraged the students' embodiment-rich interaction. While one can expect students' bodies to become involved in physics learning when explicitly requested by their teacher, I propose that open-ended student inquiry activities around large touchscreen interfaces, such as the one studied in this paper, can provide an example of a fertile environment which supports the spontaneous emergence of students' embodied engagement in the form of interaction with the technology and each other.

It may seem obvious to a teacher that more embodied interaction might take place if students are allowed the space and opportunity to stand in small groups in front of IWBs (as compared to if the same students were required to passively sit in the rows of an auditorium-style lecture hall, or interact sitting behind computer screens). However, the case study presented in Paper III (and, indeed, across this entire thesis) shows how the use of interactive technology can lead to student behavior which is productive in unexpected ways. A teacher who includes such activities into their classroom may be pleasantly surprised at the embodied engagement of their students. Learning environments spatially set up in ways that allow or even encourage student physical movement also expand the range of possibilities for student active engagement in the learning process. By doing so, such environments may serve to enhance instructional approaches that take active learning (Meltzer & Thornton, 2012) and more specifically, collaborative active learning (Johnson & Johnson, 1999) as their guiding principles.

Coming back to the role of the teacher, I recommend that teachers appreciate and become fluent in the non-disciplinary vernacular used during students' informal discussions. Meaning can be made – and consistently is made – in elaborate, multimodal ways. In cases such as the one presented in Paper III, students construct meaning in a way which capitalizes on their innate bodily intuitions. Teachers might do well to explicate the connections between student-generated embodied imagery and the relevant aspects of a phenomenon from the physics discipline's perspective. This sentiment is consonant with responsive teaching approaches (Goodhew & Robertson, 2017; Rådahl, 2017; Robertson, Scherr, & Hammer, 2015a; Robertson et al., 2015b) as well as the valuing of students' self-generated resources as compared to those resources presented by a teacher. While a teacher could reasonably propose many other semiotic resources for explaining binary star dynamics, encouraging students to come up with their own semiotic resources (and perhaps, especially, those resources which evoke vibrant embodied imagery) can benefit student learning along many dimensions. If Adam and Beth's interaction had occurred in a classroom context with a teacher present, for example, the teacher would do well to encourage the students to relate the intuitive, non-disciplinary explanation that arose with the dance to formal labels. Teaching in this responsive way is one way the teacher can help students make the metaphorical 'leap'

from intuitive reasoning to terms and mathematical relationships used in the discipline of physics. For a more detailed discussion of how a teacher might respond to students working in the environment presented in this paper, see Rådahl's master's thesis (2017).

As a word of caution, it is worth pointing out that the semiotic resource of haptic-touch should not be universally encouraged between students. The appropriateness of touch is accepted differently across different socio-cultural (and personal) contexts. Factors such as the individuals' ages (Williams & Willis, 1978), genders (D. E. Smith, Willis, & Gier, 1980), and nationalities (McDaniel & Andersen, 1998) seem to impact the degree to which those participants engage in interpersonal touch as well as their interpretation of its appropriateness. Interestingly, the setting in which an interaction takes place also seems to affect when interpersonal touch occurs spontaneously (Major, Schmidlin, & Williams, 1990; Stier & Hall, 1984; Williams & Willis, 1978). Nonetheless, and particularly as a caveat to my recommendations in this paper for the benefits of haptic-touch in Adam and Beth's interaction, it is important that the respectful treatment of students remains paramount. This includes recognizing that others' comfortability with touch may not reflect one's own.

6 Synthesis of findings

In the previous chapter I presented the data and analysis from the three papers that constitute this licentiate thesis. In this chapter, I summarize how the findings from these analyses have answered my research questions (beyond the discussions included in the previous chapter) and how the results can be synthesized across the three papers to provide meaningful insights into students' use of creative digital learning environments in small group physics work.

6.1 Research Question 1a¹

During open-ended tasks, how can sandbox-like, construction-based digital learning environments like Algodoo be observed to act as a mediator for students between the physical world and the formal, mathematical representations of physics?

My analysis presented in Section 5.1 shows how a pair of students were able to relate semiotic information across three domains (physical, formal and semi-formal) to make meaning with their talk, gesture, and interaction with the environment. Through their domain-distributed meaning-making, the students utilized a physical ramp, a creative digital sandbox, and formal representations of motion (the latter two of which were accessed through *Algodoo*). They frequently moved between these domains to construct a mathematized version of the physical phenomena of a puck rolling down a ramp, ultimately determining how the height of the ramp can be mathematically related to distance the puck travels off of the edge of the table.

While I do not claim that these students were only able to arrive at their mathematical conclusions due their engagement with *Algodoo*, I do argue that the students' use of the digital environment was a key factor in their developing an understanding of the phenomenon and the mathematically formal physics associated with it. Despite the domains having different dimensionality⁷² and varied levels of mathematical abstraction, the students frequently moved between the three domains with ease as they constructed and utilized their digital model of the physical ramp.

⁷² *Algodoo* is a two-dimensional environment, while the physical ramp takes up a three-dimensional volume.

It should be pointed out that, during the activity, I did not include any explicit discussion of the rules of the modeling “game” that the students played, contrary to Hestenes’ (1992) recommendations. Nonetheless, following the work done in this thesis – armed with a better theoretical conception of the role that creativity-driven digital environments might play in the modeling processes of physics students – I argue that software like *Algodoo* could be a useful tool for teachers to discuss modeling in the explicit manner that Hestenes suggests, and even, perhaps, for discussing the epistemological issues surrounding the use of computer-generated models in the practice of science (Greca, Seoane, & Arriasecq, 2014).

6.2 Research Question 1b ^{II}

During open-ended tasks, how can sandbox-like, construction-based digital learning environments like Algodoo be observed to provide students with alternative access to physics-relevant mathematical representations?

By appropriately encouraging and guiding students in environments such as *Algodoo*, software that are rich in the mathematical materials with which users can build and have experiences, my research indicates that it is possible for teachers to help students attain a better conceptual understanding of physics and to help them relate those conceptual understandings to mathematical formalisms. The cases presented in Section 5.2 show how the open structure of *Algodoo* inspired students to informally create and explore with formal mathematical representations.

I recognize *Algodoo* as a potentially valuable tool for expanding the possible ways in which students can engage with mathematics in physics contexts. The software allows the “object of learning” (Marton & Booth, 1997) to be presented to students as something around which they can safely and inventively build an understanding of physics phenomena. Especially when paired with large touchscreen displays such as an IWB, students using *Algodoo* may be able to experience physics phenomena through mathematical representations in much the same way that they can begin to experience velocity and acceleration in our speedometer-rich culture. By bringing mathematical representations to life within the dynamic system of a virtual world, digital learning environments like *Algodoo* might better construe representations as part of – and intrinsically related to – observable phenomena, thereby also making representations available to students as objects of inquiry. In a way, students using *Algodoo* can observe how mathematical representations behave much like one might observe an experiment.

Furthermore, while much of Seymour Papert’s work – and the well-known work of his colleague, Jean Piaget – focused on learning in young children, I argue that *Algodoo* and other open-ended software has the potential to be a

learning tool for a wide variety of students spanning many age groups. By providing a creative arena that adapts to the exploration and creativity of each user, *Algodoo* not only provides novice learners with alternative means for accessing physics, but also allows more experienced learners to further develop, assess, and/or verify their understanding of the interplay of physics and mathematics concepts. In this way, I suggest that *Algodoo* has the potential to be useful for physics learners from elementary school through university.

6.3 Research Question 1c ^{II}

During open-ended tasks, how can sandbox-like, construction-based digital learning environments like Algodoo be observed to motivate students to use physics-relevant mathematical representations?

The analysis of the cases presented in Paper II shows how *Algodoo* can provide students with non-threatening opportunities to approach problems in uniquely self-directed ways. The *Algodoo*-IWB setup studied in Paper II seems to have fostered exploratory behaviour even in relative newcomers to the software. This suggests that *Algodoo* and similar software could have potential for engaging learners in the early stages of mathematization through novel and less threatening ways than traditional instruction or classroom practices. In both of the cases presented in Section 5.2, it can be seen that, by giving students control to create and choose among the many available mathematical representations within *Algodoo* – as opposed to insisting that they use the ‘most appropriate’ representation for the task – the activity that results can be student-directed and playful in nature, while at the same time meaningful from the perspective of conceptual learning.

6.4 Research Question 2 ^{III}

How can the theoretical perspective of social semiotics be meaningfully combined with cognitive perspectives on embodiment for research on physics teaching and learning?

While there does exist research on the ways that the body underlies the metaphorical manner in which individuals think (Amin et al., 2015; Niebert et al., 2012; Roth & Lawless, 2002b; Streeck et al., 2011; M. Wilson, 2002) and research on how the body is used to communicate scientific ideas (Goodwin, 2003, 2007; Gregorcic, Planinsic, et al., 2017; Roth & Welzel, 2001; Scherr, 2008), the claims from these perspectives have only rarely been combined in the context of concrete physics examples (one instance being Azevedo & Mann, 2018). Indeed, for some researchers, this appears to have created an

immutable divide in what it means to do research of embodiment in learning (Stevens, 2012). In Paper III, I provide a methodology that incorporates the perspectives of embodied cognition and social semiotics into a single analytic framework – something which to my knowledge has not been done before. In doing so, I am able to make inferences about students’ reasoning⁷³ both in terms of non-disciplinary, embodied semiotic resources and also insofar as those resources relate to the discipline of physics. Paper III provides an example of a new analytic approach for PER scholars interested in the ways that the human body can be seen as a part of students’ thinking about, communication around, and learning of physics.

6.5 Research Question 3^{III}

Using the combined perspective from Research Question 2, how do students working in a digitally-rich environment make use of embodied, non-disciplinary meaning-making resources to reason about binary star dynamics in ways that relate to aspects deemed relevant by the physics discipline?

I answer Research Question 3 in two parts, highlighting how the students studied in Paper III (1) involved their bodies productively and (2) generated an enacted analogy.

Fruitful embodiment

In the 2.5 minutes of video data analyzed, Adam and Beth make use of non-disciplinary semiotic resources systems – including talk, gesture, body position, and haptic touch – in a manner which fruitfully involves their embodied intuitions. That is, with a close attention to the ways that Adam and Beth interact via a multimodal ensemble of semiotic resources, educational value can be seen in those non-disciplinary semiotic resources. Adam is able to communicate his mechanistic reasoning about the dynamics of binary stars to Beth in a way which encourages her to draw upon her embodied intuitions about the embodied imagery of ROTATING IN A PARTNER DANCE. Whether or not Beth has ever participated in this type of dance before, the imagery associated with the dance is strong enough that the two students are able to make use of it in their reasoning without actually completing a single turn of the dance during the interaction.

⁷³ While the particular case presented in Paper III involved students’ *mechanistic* reasoning, it is worth noting that the methodology developed and used in that study could be expected to be just as useful in cases that do not involve mechanistic reasoning. For example, the approach could have been fruitfully applied to – and was in fact inspired by – datasets that include student engagement that mostly does not involve mechanistic reasoning (Gregorcic, Planinsic, et al., 2017).

The non-disciplinary semiotic resource systems, particularly the non-verbal semiotic resource systems of body position and haptic touch, make the enactment of a relevant counterfactual (the ‘over-rotation’ in the dance) possible. Adam is then able to talk and gesture around this embodied act to draw Beth’s attention to particular features of the situation, thereby resulting in a complex, multimodal utterance which communicates to Beth far more than would be possible with talk alone. This observed behavior is consonant with Goodwin’s (2003) discussion of the way in which talk and gesture can *mutually elaborate* one another. The data in Paper III provides an example of students leveraging many distinct semiotic resources across different semiotic systems in their spontaneous (self-directed) interaction which contribute to the construction of a communicational whole – and which goes beyond the parts themselves. Insofar as the physics education community values students’ construction of explanatory models for physics phenomena, physics educators should acknowledge the potential for non-disciplinary semiotic resources to leverage students’ embodied intuitions in pedagogically fruitful ways.

Generation of an enacted analogy

As discussed in Section 5.3, mechanistic reasoning entails the development of explanatory models. Etkina et al. (2006) suggest that “explanatory models are based on analogies – relating the object or process to a more familiar object or process” (p. 34). This is precisely what Adam and Beth are seen doing as they mechanistically reason via non-disciplinary semiotic resources: they generate for themselves an enacted analogy for the orbits of binary stars in the form of an embodied dance.

Haglund and Jeppsson (2012) provide a useful discussion on the potential benefits of students’ self-generated analogies in the physics classroom, wherein they show how self-generated analogies have the potential to increase students’ ownership of learned material (see also, Dudley-Marling & Searle, 1995; Milner-Bolotin, 2001). This seems to be the case particularly when those analogies are taken up in small group discussion (Enghag et al., 2009; Enghag & Niedderer, 2008). Heywood and Parker (1997) show – and Haglund and Jeppsson’s (2012) findings support – that the student-generated analogies which involve a high degree of correspondence between the source and the target domains generate rich discussions amongst the students.

I view the emergence of Adam and Beth’s enacted analogy as consonant with these findings about students’ self-generated analogies. The dance (source domain) corresponds highly – for the purpose of answering the question about orbital periods – with the binary star system (target domain) and my analysis demonstrates how the students’ discussion that surrounds this analogy is certainly rich. In this way, Paper III highlights how non-disciplinary semiotic resources are a worthwhile component to students’ generation of analogies. Haglund and Jeppsson (2012) explain that when students discuss their own self-generated analogies (rather than when discussing an analogy

supplied by an teacher), they are more “aware that the sources are not perfect matches to the targets” and, thus, might be more likely to scrutinize their analogy and explore its limits (p. 917). With the analysis conducted in Paper III (Section 5.3.4), I have highlighted non-disciplinary semiotic resources as a potentially necessary piece to students generating and taking up analogies of their own. For example, in line 89 from Paper III (p. 112), Beth acknowledges that the two stars are attracting each other “in some way” as she gesturally alludes to the dance and the IWB. Beth uses non-disciplinary resources – especially as opposed to involving the concept of ‘gravity’ directly – as she begins to adopt the analogical link between the dance and the binary star system. Her acceptance of Adam’s dancing analogy for the binary stars hinges on her using relatively ‘loose,’ informal language alongside gesture and gaze-based reference to the simulation on the IWB.

6.6 Synthesizing across the three papers

Taken together, the work of this licentiate thesis can be conceptualized as the exploration of an ‘ecosystem’ of digitally-rich physics meaning-making: specifically, the papers of this thesis have in one way or another explored the relationships between a *Controllable World* (running on an IWB), a small group of students, and the physical world (Figure 32).

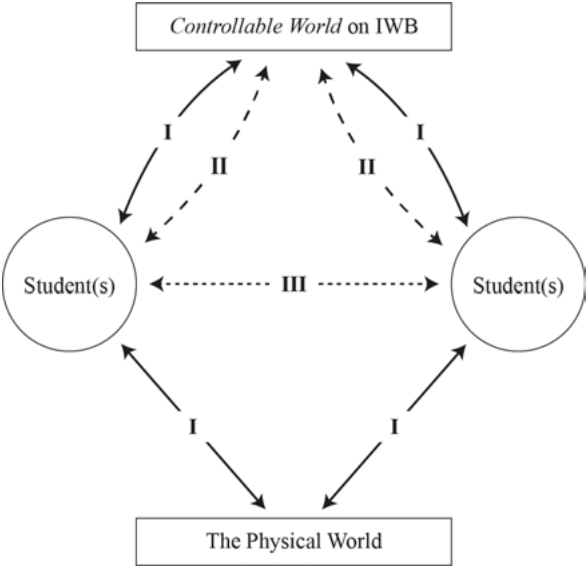


Figure 32. A graphical summary of the ‘ecosystem’ explored in the three papers that make up this thesis. The arrows represent the exploration of the relationships between the various constituents of the ‘ecosystem’ and are labeled with the roman numeral of the paper in which this exploration was carried out. The dotting of the lines is used in combination with the roman numerals to distinguish between the three papers.

In Paper I, I explore the relationship between *Algodoo* and the physical world (as mediated by students). In doing so, I reveal how students can be observed to move between *Algodoo* and the physical world through their multimodal interactions with the environment. Furthermore, *Algodoo* is seen to be the locus of both semi-formal modeling and also physics formalisms for the students. I show how the degree to which students' modeling occurs can also be noticed (by teacher or researcher, alike) through an attention to the details of students' moment-to-moment communication and interaction with the software.

In Paper II, I explore the relationship between *Algodoo* and the students. To do this, I employ the concepts of constructionism and microworlds to show how students could make use of the mathematical materials within *Algodoo* to make sense of physics phenomena. The analysis of students' gestural activity around the IWB in combination with their talk reveals how mathematical representations can be used by students in unconventional, yet meaningful ways.

In Paper III, I explore the relationship between the students themselves (against the backdrop of *My Solar System*). I combine the perspectives of social semiotics and embodied cognition in order to interpret the informal meaning-making of students as they reasoned about a physics phenomenon. Using this framing, I produce a nuanced description of how students can incorporate their bodies while doing physics, especially in a digitally-rich environment.

The work of this thesis represents my effort to take a closer look at the processes of meaning-making that can occur moment-to-moment while students engage with physics content. Especially as compared to the types of PER projects which might issue pre- and post-tests to track students' learning gains or conceptual mastery via assessment tools, I have opted to focus instead on the mechanisms of meaning-making which occur *between* the 'pre' and 'post.' In doing so, I have been able to meaningfully contribute to the theoretical picture of students' meaning-making in digitally-rich physics learning environments. Across all of the studies presented in this thesis, I have consistently shown how the use of interactive technology like *Algodoo* or *My Solar System* on an IWB can lead to student behavior which is productive in unexpected ways.

7 Contributions and implications

In the preceding chapter, I discussed the findings and results of this licentiate thesis both in terms of my research questions and also as a whole across the three papers. In this chapter, I provide a brief summary of the ways in which this thesis contributes to PER – both theoretically and methodologically – as well as a list of the implications for the teaching and learning of physics.

7.1 Theoretical contributions

In contribution to theories pertinent to PER, this thesis

- provides an example of students observably making use of a digital learning environment in a manner consistent with that of a semi-formalism;
- meaningfully combines the notion of semi-formalisms with the modeling framework to propose a notion of semi-formal modeling in digital learning environments;
- articulates the ways in which construction-based software such as *Algodoo* can function as a physics microworld for students as they playfully explore in open-ended tasks;
- demonstrates the potential viability of microworld-like software when dealing with certain topics of physics at the upper-secondary and/or introductory university levels;
- meaningfully combines the theories of social semiotics and embodied cognition into an analytic perspective in terms of embodied imagery and disciplinary-relevant aspects;
- demonstrates a potential need for the rethinking of embodiment in physics, which goes beyond labels such as kinesthetic learning activities and/or embodied learning activities on smaller time scales of student interaction;
- expands social semiotic theory by providing an example of (non-visually-persistent) embodied imagery serving as a hub around which other physics-relevant semiotic resources can be meaningfully coordinated.

7.2 Methodological contributions

Methodologically, this thesis

- demonstrates how conversation analysis can be meaningfully applied to study the physics students' interactions, especially on a moment-to-moment basis;
- provides three examples of how to incorporate multimodal transcriptions of data into publications (with two additional full transcripts included in the appendices);
- provides an example how a wide range of students' meaning-making resources – especially those beyond talk, such as gesture, interaction with the environment, haptic touch, and body position – can be studied in physics learning contexts;
- showcases a technique for the presentation of multimodal data, namely that of vector-based line illustrations, which may be preferable to pictures or frames of video for the matters of highlighting and anonymization;
- demonstrates how students' multimodal utterances can be fruitfully interpreted in terms of embodied imagery, and how this embodied imagery can be systematically related to the aspects of a context deemed relevant by the discipline of physics.

7.3 Implications for the teaching and learning of physics

In regards to the teaching and learning of physics, this thesis

- provides a “thick description” (Geertz, 1973) of students interacting with physics-relevant examples in and around digitally learning environments, such that these types of creative activities might be implemented in physics or astronomy courses;
- suggests how a discussion on the topic of modeling (as treated by Hestenes (1992), for example) could leverage software such as *Algodoo*;
- explains the manner in which digital learning environments like *Algodoo*, especially when run on an IWB, have the potential for engaging learners in the early stages of mathematization through novel and less threatening ways than traditional instruction;
- develops a potentially useful perspective for viewing student interaction wherein a teacher can better understand the students' rationale by attending to the non-spoken aspects of students' meaning-making;
- suggests that teachers can frame an activity technologically (with large touchscreen interfaces and creative software) and epistemologically (with open-ended activities) such that students might be encouraged to participate in more embodiment-rich interaction;

- invites teachers to appreciate and value students' informal meaning-making in physics, especially since non-disciplinary resources can be (and most assuredly *are*) used by students to interpret the disciplinary content of the physics classroom.

8 Future work^I

This licentiate thesis represents the initial work toward my doctoral thesis. While there are certainly many directions in which I could expand on the work presented here and in Papers I, II, and III, I will use this final chapter of the thesis to discuss one such route that I have already begun exploring.

One of the critiques of the use of *Controllable Worlds* in physics learning (especially as substitutes for physical laboratory work) is that students are presented with all of the important and relevant features of a phenomenon and, thus, never encounter the *messiness* of traditional laboratory work (Bryan, 2006; Chinn & Malhotra, 2002). Indeed, the design and execution of laboratory investigations involves the particularities of apparatuses and the treatment of error. In future work, I am interested in exploring how more open-ended, construction-driven software like *Algodoo* might allow for a messier inquiry than some of the more structured simulations. I expect that appropriate use of software like *Algodoo* might entail a higher degree of messiness by requiring that students make modeling and representational decisions and by allowing them the freedom to explore and investigate their own models' behavior through construction and deconstruction. Still, as compared to the physical world, I suggest that *Algodoo* might provide more direct (less messy) access to some formal representations, such as graphs, without the need for students to perform the process of measurement (which, in itself, is a messy procedure). To this end, a potential research question for my future work is:

What are some of the ways in which students become aware of physics concepts and develop physics content knowledge as they use Algodoo for the first time?

In answering this question, I plan to involve a theoretical lens which has yet to feature in my research, namely the Variation Theory of Learning (Marton & Booth, 1997). I intend to draw on Variation Theory because of its applicability to the topics of messiness and students' awareness of physics concepts. Variation Theory has previously been combined with social semiotics in the context of physics (e.g. Airey, 2009; Fredlund, 2015; Fredlund, Airey, et al., 2015; Fredlund, Linder, et al., 2015a, 2015b) as well as once before as an analytic tool in the context of digital tools (Ingerman, Linder, & Marshall, 2009). Thus, moving forward in my doctoral thesis, I plan to build on this previous research in combination with the theoretical ideas developed in this licentiate thesis.

Acknowledgements

This licentiate thesis would not have been possible if not for the support and collaboration of many other people. To my supervisor, Bor, thank you for your unrelenting passion for my project. Your willingness to work closely and consistently with me has been a real joy, thus far. You have already helped me craft a body of work of which I am quite proud and I consider myself extremely lucky to have such an outstanding supervisor such as yourself at my back. To Cedric, thank you for lending your invaluable expertise – both in terms of your PER knowledge and also your seasoned skills in navigating the academic landscape. You have offered essential feedback on my writing numerous times, this thesis included, and you have been a constant advocate of my doctoral work. I am very grateful for all you have done and continue to do for my studies. To Trevor and Robin, thank you for providing me with immediate friendship and well-needed discussions around the onslaught of PER topics we encountered the first few months of our studies (and since). To Johanna and Anders, thank you for efforts to expand my academic and personal horizons in this strange new world of Uppsala and for your gracious hospitality. To James, thank you for the unending laughs, musically-rich tangents, and consistent servings of humble pie. To Moa, thank you for your help with checking Swedish translations and, more importantly, for your untiring friendship that has continued to breathe so much liveliness into my time at and away from work. To Anne, thank you for your immeasurable contribution to the Uppsala PER group and your willingness to always lend a helping hand. To John and Jesper, thank you for your tremendous expertise and invaluable feedback on much of my writing. To Filip, thank you for making sure I laugh every single day; I am so glad to have worked with you before you retired. To the entire Uppsala Physics Education Research Team, thank you for all of the feedback, all of the help with drafts, all of the assistance with analyses, and the culture of excellence each of you maintain in our group. I wholeheartedly enjoy my doctoral work and this is in large part due to you all being such great coworkers and exceptional people.

To Desirae, thank you for your love, patience, and daily encouragement. To my parents, thank you for inspiring me to keep learning and for showing me the power of science, mathematics, and education. To Jake, thank you for helping me maintain some sort of balance in my life through our creative collaborations.

Perhaps more significant than the academic work presented in this thesis, the last two and a half years have been a grand adventure in personal growth. To all of my new colleagues here in Sweden, thank you for your constant encouragement to push myself, try new things, become more aware of the world, and reflect on myself. To my friends and family back in the U.S., thank you for your constant support from afar and patience as I continue to adventure abroad.

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Appendix A

Consent forms used for the
first data set



Participation in a study of the use of digital technology in physics

The Division of Physics Education Research at the Department of Physics and Astronomy, among other things investigates the manner in which new technologies in teaching and learning physics are used. This research is crucial to the development of how physics is taught. This is especially relevant as our daily lives become increasingly permeated with ever-new technologies.

This autumn, we are conducting a research project to explore the ways in which a digital sandbox software, *Algodo*, is used as a modeling device for physics phenomena. We are interested in how you, your peers, and other physics learners like you interact with this software while experimenting in physics. Your possible contributions to this research project would be of great value to our group at UU and the broader community of physics education researchers.

What's the purpose of this research?

This study is part of Elias Euler's PhD project, which focuses on the disciplinary and pedagogical affordances of digital technologies in relation to the teaching and learning of physics. The use of digital tools to facilitate teaching and learning in the classroom is a growing research area but studies addressing the use of digital tools in physics are still scarce and in high demand. This study aims to expand on the existing knowledge about technology use in the classroom by comparing and contrasting the ways in which the *Algodo* software is used alongside a traditional laboratory exercise.

How can you contribute?

To examine the ways in which you use digital software such as *Algodo* in your process of physics problem solving, we would like to record you and a partner completing a physics experiment with a physical experiment setup as well as with the help of a computer with *Algodo* software. Elias will meet with each pair of participants for a short instructional session to familiarize you with the *Algodo* software and then participants will complete the activity with Elias acting as an observer and facilitator. Following the completion of the activity, a short interview will be conducted reflecting on the activity. Completion of this sequence will earn each participant a voucher for a pair of movie tickets.

What does participation mean for you?

If you choose to participate, you accept that the data collected through your participation will be used for physics education research at Uppsala University. The data will be used to explore the use of digital technology in the teaching and learning of physics. At any time, you can request a copy of all information pertaining to you and/or you can choose to withdraw your further participation in the study.

(see other side for more information)

How is the research done and how will the material be treated?

We will collect the data for our analysis by audio and video recording the activities listed above. Transcripts from the Algodoo training session, the physics activity, and the interviews will be used to analyze the activity using theories and concepts concerning education and the use of technology, among others. The anonymized texts may be discussed with the Physics Education Research group at UU and their research colleagues when preparing publications based on this study.

Personal information such as your name, address, phone number, or any other information, which can connect you to the study will not be present in the compiled transcripts used for analysis but rather kept separate. You will be given another form of identification if referred to directly in any of the analysis – such as an index number. If there is a risk that you might be identified in video frame, your appearance will be censored unless otherwise agreed upon after the fact. If your personal information might be inferred from a specific episode of the activity, that episode will be avoided in any publication.

According to Swedish law we are required to archive research material. The material from this study will be archived in a secure way on encrypted or locked up media and no unauthorized person will have access to the material. The results of this study will be published in academic journals and in a dissertation. The study will also be discussed at scientific conferences, potentially before and after publication.

All specifics aside, we are very excited to work with you on this project! Please contact Elias directly if you think this study is something you would be interested in!

Contact

To contact us with any questions or concerns – or if you would like to volunteer! – please use the information below.

Elias Euler
PhD Student in Physics Education Research
Elias.Euler@physics.uu.se
0732-426 697



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Consent to participation in a scientific study

The Physics Education Research group at the Department of Physics and Astronomy, at Uppsala University is conducting a research project to explore the ways in which a digital software, *Algodo*, is used as a tool in learning physics. We are interested in how you, your peers, and other physics learners like you interact with this software while experimenting in physics!

Conditions of participation

We would like to record you and a partner completing a physics experiment with a physical experiment setup as well as with a computer running the *Algodo* software. As a participant of this study, you are asked to attend a short session where the researchers will teach you how to use the *Algodo* software as well as complete a physics activity with one other participant (while under the observation of a researcher). Following the completion of the activity, a short interview will be conducted reflecting on the activity. The *Algodo* training, physics activity, and subsequent interview will be recorded with video and audio equipment.

How is the research done and how will the material be treated?

In the interest of treating all participants ethically, the research team will handle the data collected as part of this study in accordance with established Swedish research ethics.

It is important that you understand how your integrity and your personal information will be protected throughout the entire research process. Personal information includes data like your name, address, phone number, or any other information, which can connect you to the study. This kind of information, if collected, will not be present in the compiled transcripts used for analysis but rather kept separate. You will be given another form of identification – such as an index number if/when referred to in the analysis of the data.

If there is a risk that you might be identified in video frame, your appearance will be censored. If your other personal information might be inferred from a specific episode of the activity, that episode will be avoided in any publication, unless we obtain your separate and written permission to use such episodes for publication purposes. At any time, you can request a copy of all information pertaining to you and you can choose to withdraw your participation anytime during the study. In case of withdrawal, we may still use the data already published, in accordance with the above stated principles regarding the protection of your integrity and personal information.

According to Swedish law, we are required to archive research material. The material from this study will be archived in a secure way on encrypted or locked up media and no unauthorized person will have access to the material. The results of this study will be published in academic journals and in a dissertation. The study will also be discussed at scientific conferences, potentially before and after publication.

If you agree to the described use of research data and you are willing to participate in this research study, please sign below.

Name (printed)

Signature

Date



Additional consent to use of uncensored video

(recorded as a part of the research project on the use of Algodoo software in physics learning)

Following the completion of today's activity, you should have a better idea of the sensitivity of the information shared.

The analysis of the data collected in this study will include, among other things, a discussion of how you and your partner (the participants) used your hands to gesture and interact with the objects during the activity. In the previous consent form, it was explained that all data will be anonymized such that no identifying information is shared with anyone outside of the immediate research team; however, we would now like to ask if you would allow the use of uncensored video in publications and presentations to the public.

The inclusion of uncensored video clips (and/or GIFs) in the published materials from this study would allow the research team to make much stronger claims about the ways in which you and your partner communicated ideas. Most of the existing research on gesture analysis includes static, censored images (if at all), so the inclusion of entire, dynamic clips of your interactions today could prove to be especially groundbreaking in the field.

The research team will still refrain from publishing any other personal information such as your name as per the previous consent form. It should also be known that we are not trying to embarrass or make fun of any of the participants in this study. Wherever possible, we will use video data that shows as few identifying features as possible and will refrain from using any data that we think may potentially portray any participant in a less favorable light.

Extended consent

Please indicate below your level of comfort with the use of uncensored video in publications or presentations (please select one):

- ☐ I allow the use of my full likeness in video data, including my uncensored face and body, in scientific publications or presentations.
- ☐ I allow the limited use of my likeness in video data. Specifically, I allow the use of uncensored video of
 - my face ☐ yes ☐ no
 - my body (not including my face) ☐ yes ☐ no
- ☐ I do not allow the use of my likeness, in publications or presentations as per the previous consent form.

Please sign below after designating your consent to use of video data above.

Name (printed)

Signature

Date

Appendix B

Consent form used for the
second data set

Obveščeno soglasje k sodelovanju v raziskavi

Raziskava: Preiskovanje prednosti interaktivnih tabel in njihova uporaba pri pouku fizike

1. Vabljeni ste k sodelovanju v raziskavi Preiskovanje prednosti interaktivnih tabel in njihova uporaba pri pouku fizike, ki jo v okviru doktorske naloge izvaja Bor Gregorčič, mladi raziskovalec. Raziskava poteka na Oddelku za fiziko, Fakultete za matematiko in fiziko, Univerze v Ljubljani, pod vodstvom prof. dr. Gorazda Planinšiča. Namen raziskave je raziskati učinkovite načine uporabe interaktivne table pri pouku fizike in izsledke uporabiti za razvoj učnih vsebin.
2. Če se odločite za sodelovanje v raziskavi, bo vaša naloga obiskovati pouk in občasno izpolniti vprašalnike o učnih urah, ki ste jih obiskali. Sodelovanje v intervjujih ali delu v manjših skupinah je prostovoljno.
3. Izvedba preizkušenj bo trajala celo šolsko leto z vmesnimi (lahko tudi več mesečnimi) presledki. Za udeležbo v raziskavi ne boste prejeli nobenega nadomestila.
4. Udeležba v raziskavi ne prinaša posebnih tveganj.
5. Sodelovanje v raziskavi ne prinaša posebnih koristi z izjemo znanja in izkušenj, ki jih boste pridobili v okviru sodelovanja.
6. Vaše sodelovanje v raziskavi je v celoti prostovoljno in ga lahko kadarkoli prekinete brez posledic.
7. Storili bomo vse, da zaščitimo vašo zasebnost. Zapisi vaših izkušenj in spremljajoči demografski podatki (starost in spol) bodo shranjeni pod raziskovalno šifro. Vaša identiteta v nobenem primeru ne bo razkrita.
8. V primeru morebitnih dodatnih vprašanj se lahko obrnete na raziskovalca Bora Gregorčiča (bor.gregorcic@fmf.uni-lj.si) ali na Komisijo Republike Slovenije za medicinsko etiko.

S podpisom jamčim, da sem izjavo prebral/-a in da sem dobil/-a priložnost za postavitev vprašanj v zvezi z raziskavo. Potrjujem svojo privolitev za udeležbo v opisani raziskavi, "Preiskovanje prednosti interaktivnih tabel in njihova uporaba pri pouku fizike" ter dovolim uporabo rezultatov v pedagoške in znanstveno-raziskovalne namene.

_____ Ime, priimek in podpis udeleženca	_____ Datum
_____ Ime, priimek in podpis skrbnika	_____ Datum
_____ Ime, priimek in podpis izvajalca raziskave	_____ Datum
_____ Ime, priimek in podpis vodilnega raziskovalca	_____ Datum

Raziskavo je dne 30. 7. 2013 odobrila Komisija Republike Slovenije za medicinsko etiko.

Appendix C



Consent forms used for the
third data set



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Medgivande att delta i en vetenskaplig studie

Som mitt examensarbete kommer jag¹ och min handledare², i samarbete med forskargruppen inom Fysikens didaktik vid Uppsala universitet, att genomföra en studie med syfte att undersöka hur gymnasieelever kan lära sig fysik med hjälp av digitala verktyg och simuleringar inom ämnet astronomi. Vi är intresserad av hur du, dina klasskamrater och andra fysikstuderande interagerar med mjukvaran som en del av en lärandeaktivitet.

Villkor för deltagande

Om du väljer att delta i denna studie kommer du, tillsammans med en kamrat, att få besöka oss på Ångströmlaboratoriet där du kommer att få en introduktion till programmet *Algodo* samt Phet's simulering "My solar system", och därefter genomföra en aktivitet om Keplers lagar. När vi är klara avslutar vi med en kort intervju där du får reflektera över aktiviteten. Introduktionen, laborationen samt intervjun kommer att filmas med videokamera och beräknas ta cirka två timmar.

Hur genomförs forskningen och hur kommer det insamlade materialet att behandlas?

För att se till att alla deltagare behandlas etiskt kommer datahanteringen i denna studie ske i enlighet med etablerad svensk forskningsetik.

Det är viktigt att du förstår hur din personliga information och integritet kommer att skyddas under hela processen. Personlig information innefattar data som ditt namn, adress, telefonnummer, eller någon annan information som kan koppla dig till denna studie. Om någon sådan information samlas in kommer den inte att finnas med i det transkriberade analysunderlaget, utan kommer istället att lagras separat. Du kommer att identifieras med ett påhittat namn om/när det hänvisas till dig i analysen av datan.

Om det finns risk att du kan identifieras utifrån en video-bild kommer den att censureras. Om annan personlig information kan härledas ur ett visst avsnitt av aktiviteten så kommer den inte finnas med i någon sorts publikation, om vi inte får ett separat skriftligt tillstånd att offentliggöra sådana episoder. Du kan när som helst kräva en kopia av all information som rör dig och ditt deltagande och du kan välja att avsluta ditt deltagande när som helst under aktiviteten. Väljer du att avbryta ditt deltagande under studiens gång kan vi fortfarande komma att använda den data som vi samlat in, i enlighet med principerna ovan.

Enligt svensk lag är vi tvungna att arkivera forskningsmaterial. Materialet från denna studie kommer att arkiveras på ett säkert sätt på en krypterad eller på annat sätt låst hårddisk och ingen obehörig person kommer att ha tillgång till materialet. Resultatet av denna studie kan komma att publiceras i akademiska journaler eller i en avhandling. Studien kan även komma att diskuteras vid vetenskapliga konferenser före eller efter publikation.

Om du samtycker till denna beskrivning av användandet av forskningsdata och är villig att delta i denna forskningsstudie, vänligen skriv under nedan.

Namn (textat)

Signatur

Datum

¹ Elmer Rådahl, elmer.radahl@hotmail.com

² Bor Gregorcic, bor.gregorcic@physics.uu.se



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Ytterligare medgivande för användning av ocensurerad videodata

(insamlat som del av ett forskningsprojekt om användning av digitala verktyg inom fysikinläring. Kontaktpersoner Elmer Rådahl¹ och Bor Gregorcic²)

Efter slutförandet av dagens aktivitet bör du ha en bättre uppfattning av hur pass känslig den insamlade informationen är.

Analysen av den insamlade datan från denna studie kommer, bland annat, inkludera en diskussion om hur du och din partner interagerade med simuleringarna och med varandra. I den tidigare medgivande-blanketten förklarades det hur all data kommer att anonymiseras till den grad att ingen identifierande information kommer att delas med någon utanför forskningsgruppen; vi vill dock nu fråga om du vill tillåta användandet av ocensurerad video i publikationer och presentationer till allmänheten.

Användandet av ocensurerade bilder eller videoklipp i det material som publiceras från denna studie skulle kunna låta forskargruppen beskriva hur du och din partner kommunicerade mer ingående. Majoriteten av nuvarande forskning om studenters användande av teknologi använder sig av statiska, censurerade bilder, så användandet av dynamiska videoklipp från dagens aktivitet skulle kunna vara banbrytande inom forskningsfältet.

Forskningsgruppen kommer fortfarande låta bli att publicera någon annan sorts personlig information, i enlighet med den tidigare medgivandeblanketten. Närhelst det är möjligt kommer vi att använda videodata som visar så få identifierande drag som möjligt och vi kommer att avstå från att använda data som vi tror kan porträttera deltagaren på ett negativt sätt.

Utökat medgivande

Vänligen indikera nedan din grad av villighet att tillåta användande av ocensurerad video i publikationer eller presentationer (välj endast en):

- ☐ Jag tillåter användandet av video av mitt ocensurerade ansikte och min kropp, i vetenskapliga publikationer och presentationer.
- ☐ Jag tillåter ett begränsat användande av videodata. Mer specifikt så tillåter jag användande av ocensurerad video av
 - mitt ansikte ☐ ja ☐ nej
 - min kropp (inkluderar ej ansikte) ☐ ja ☐ nej
- ☐ Jag tillåter inte användandet av mitt ocensurerade ansikte och min kropp, i vetenskapliga publikationer och presentationer.

Vänligen skriv under nedan efter att ha bockat för en av rutorna ovan.

Namn (textat)

Signatur

Datum

¹ Elmer Rådahl, elmer.radahl@hotmail.com

² Bor Gregorcic, bor.gregorcic@physics.uu.se

Appendix D



Transcript from the first data
set

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
0:56:12							So yeah, you can- you can just choose whatever technique you want. It's up to you to decide what you're- how you're going to proceed. And the thing is... you can use both this and that. It's- we would like you to... try and... uh, to your best... um... idea, combine the physical experiment and you can help yourself with the Algodoo software if you have stuff you wanna try out- whatever. So, but it's gonna be up to you to decide how you're going to use them.	
	I don't- I don't see how we could combine both of them. Like, either you-							
							(Interrupting) So maybe-	
	-use the physical OR you use the non-physical way because you cannot merge virtual world and non-virtual world.					Draws a rectangle on the Smartboard		

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
						(Pauses to listen to R1) now tries to rotate the rectangle with several motions on the board	(Pause) ... But um... Go on. Go on. (to 21102, for them to keep drawing on the Smartboard) the task is quite general, so we're not asking you to show us the relationship for just this ramp, right? We wanna know in- more in general.	
						(Pauses again) now draws a drcie above the tilted rectangle		Like if I have a ramp somewhere and something rolling down it off of some edge, how far will it go based on how high it is up on the ramp or the- the slope?
							So you want to move things around, you need the pen tool... when it's PAUSED- when it's paused.	
							And if you wanna s- do you want this rectangle to be there?	
				Yes.			Then you can just double click on it	
						Tries to double tap the rectangle		
						Successfully double clicks the rectangle, opening a drop-down, menu.	...Uh again. And then go to geometry actions... about, fourth from the bottom.	

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
			Points to the "geometry actions" bar on the drop down menu (on the Smartboard)				Yeah. And then select geometry actions.	
	Above the (indistinguishable).							
							And then glue to the background. Yeah.	
				Ah.				And now it won't... uh fly- it won't fall down. It's part of the environment now.
				K. Let's... try this.		Presses the play button to run the simulation		
						Waits for the circle to roll down the ramp and hit the ground and then points to the spot on the board where it appeared the circle landed		
				About here, right?				
	Yeah something like that.							So one important thing here is, uh... this extra- extra part right here (points with the meter stick to the part of the table after the bottom of the ramp and before the edge of the table) to know that the velocity is going exactly horizontal at the end.
				Okay.				
								Does that make sense?

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
	So then we should add...							
			Selects rectangle tool on the Smartboard					
	...another... rectangle.		Draws a small rectangle next to the tilted rectangle drawn by 21102					
				Bigger. Maybe? Mm, okay.				
	That doesn't really matter.		Moves new rectangle so that the top-left corner is intersecting the top right corner of the tilted rectangle.					
			Continues moving the rectangle.		Moves hand downward while gesturing toward the second rectangle			And if you glue things to the background, um... they can overlap each other.
			Continues moving the rectangle.	Move it down. ...A bit. Yeah.	Repeats gesture, holding hand out to show they are still concerned about the placement.			
			Opens drop down menu and selects "glue to background" option	Glue it.				
				Alright.		Presses the play button to start the simulation.		
	Landed about, here I would say.		Points to spot on the board where the circle landed on the ground.					

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
			Accidentally deletes the ground by selecting it and then swiping over while trying to point to the spot. Presses undo until the ground comes back and the ball is returned.					
	(Laughing) Do not remove Earth.			(Laughs)				
	So...							
				Then we-		Gestures with hand to show moving all of the shapes upward on the board.		
	(Interrupting) The- the- the main question to answer is, like, how much we have to tilt this one and what difference does that it will make to how far-		Picks up the physical ramp and tilts it to demonstrate their point, holding the ramp in the upward position.					
			Holds the ramp .			Tries to select all of the shapes on the board by encircling them with their finger.		(Interrupting) Yeah. What's the relationship between how high the ball- the puck starts and how far it goes?
			Puts the ramp down.			Tries again.		
								So not-
							Pen.	
				Pen...				
	Pen tool.	Points vaguely toward the top of the tool bank on the board.						
				I want to mark all them.				
						Selects pen tool and then encircles all of the shapes.	Mm hm.	

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
	But that would just make it... increase upwards.	Moves both hands upward while holding them horizontally to show "upwards but not tilting"						
				Yeah but I want to move all them upwards.	Points and moves arm upward			
	Yeah because-			Or down-	Moves arm downward			
	But that doesn't matter because in the physical experiment you only increase the height like this. So we are actually just rotating the pink one.	Picks the physical ramp up again and lifts one end to show the ramp rotating rather than translating upward		Mm.				
				Okay.	Looks back at the Smartboard.			
	So we just-							Yeah not the- the overall height above the floor of the...
				Oh. Right.				
							So the table stays where it is.	
	Yeah so instead, do like...		Selects the rotate tool and then selects the "pink" rectangle					
			Rotates the rectangle about the center point.	Just rotate that one.	Points vaguely toward the larger rectangle (pink one)			
	Uhh...		Continues rotating and then stops. Presses the undo button					
	Let's see... Is there any way for this software to change the center of rotation?							

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
								I don't think so, is there?
						Tries to rotate the rectangle again.		
							Where would you like the center of rotation to be then?	
	Uhh...		Points to the bottom of the physical ramp.					
	Down here.							
							Ah okay.	
	So that we can... mimic it in the real world.	Gestures with both palms flat, moving in opposite directions up and down to suggest tilting					Mm hmm.	Mm.
			Goes back to the Smartboard and selects the rectangle and double clicks to bring up the drop down menu. Then, while Bor is talking, looks at the options available on the menu.				I think, there- we can try- so we can try something I'm not sure it will work but there's one way you could do this.	
	Uh huh?		Still examines the menu.	K.				
			Selects the "geometry actions" tab and bends to look at the options			Moves to tap outside the menu to get rid of it	And that is if you zoom in to that end of the, uh-	
	Ah wait, here.		Places center axle on the rectangle.					
								So that-
			Tries to select just the center axle.				Yeah that was exactly what I was thinking. But you... so how did you find this? You noticed this before.	
	No. I just guessed.		Continues to try to select the axle.					

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
							Ah okay. So-	
	Geometry actions... add center axle.		Clicks through the menu like before to show where the center axle came from					
							So this is CENTER axle.	
	Yeah.			<i>(Mumbles something indistinguishable)</i>				
							So if you remove this one... if you....	
	Take that one.		Tries to select the center axle, then selects pen tool.					
			Tries to select the center axle again, and then the pen tool. Tries to move the axle to the upper right corner of the rectangle.				No-	I think this one's stuck to the center of the...
			After a couple of tries finally gets the axle to move.				No this one's actually stuck to the center because-	
								Oh my gosh....
							Oh! This is brilliant. <i>(Laughs)</i>	
	Whoops. Let's just move that one... And then take this one... and move it, there.		Deselects the axle, moves the smaller rectangle out of the way, and then reselscts the axle to place it on the corner of the larger rectangle.					
				Mm hmm.				
	And then move this one and have it above the center axis.		Moves the smaller rectangle back to overlap the end of the larger (tipped/pink) rectangle					

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
	And...			And try to rotate.				
	Yeah.					Selects the rotate tool		
			Selects the larger rectangle and rotates it around the new point of rotation as desired					
01:02:54	This works perfectly!		Shows the full range of rotation of the rectangle (360 degrees)					
	So now we can increase this one as much as we would like and the only thing we'll have to do is-		Moves the angle of the rectangle's preliminary orientation					
				Move the ball.				
	Yes.		Selects the pen tool and moves the circle upward					
	So let's say we increase it to that. But we also need some way of measuring how far it goes. And that would be best done by...		Rotates the rectangle to meet the bottom of the ball and then steps back to try and find some tool that hasn't been found yet					
	What does this one do?		Selects some buttons from a side menu of Smartboard actions					
								Oh those are like, Smartboard-
	Smart board features.					Oh yeah.		
								So yeah...
	So is there any to like paint colors that are nothing, are just colors.	Moves hands with fingers splayed in circular motion while saying "paint colors"						
							Oh to just mark something?	
	Yeah.							

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
						Double clicks the circle, and examines the drop down menu until they find the "plot" option	Unfortunately, this software doesn't do that.	(Overlapping) Yeah...
01:03:47				You can plot.		Points to the graph that they have produced for 21102 to see	But you can actually make STUFF draw stuff.	
	Yeah.							
	Make stuff draw stuffs?					Examines the plot menu.		
						Clicks on one of the axis values and examines the options	Yeah. Stuff that moves there can draw stuff. It can....	
	Okay...					Hovers their hand over the options		
							Yeah. So you can track actually where-	
								So you can track where the- where the ball went.
							On the background.	
	(Overlapping) And we could also do... this.		Points toward the graph on the board			Selects one of the options.		On the background as it plays. Yeah yeah.
						Hovers their hand over the options		Mm hmm.
	Which would show us... We need the position-y, otherwise we will not be...							
						Clicks on the position-y option and then changes the other axis to the desired option (position-x)		

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
			Moves to the board and resizes the graph window before dragging it across the board to the left side so the ball-ground contact can be observed					
	Something like that... I think.							
	Yeah.			Aaand start?				
						Presses the play button to start the simulation, then pauses the simulation when the ball has circle has rolled away.		
	Ahh, let's see. If we look closer at this.		Bends to examine the graph from closer up					
			Clicks on the graph region to select the specific data					
				Here.		Points to the spot on the graph they think the circle hit the ground		
	Yeah there.	Steps back from the board.						
	We can see that...							
	We have to look at it from here to there.		Points to the part of the graph where the circle left the horizontal rectangle to the point where they think the circle hit the ground					
				Hits the ground there. That's what we want to get.		Points to the spot on the graph where they think the circle hit the ground.		

Timestamp	S1			Interaction with Objects	S2			Interaction with Objects	R1	R2
	Talk	Gesture			Talk	Gesture				
	Yeah, we want to know the distance... here.	Points to the table, places their hands together, and then spreads them apart to show where the distance starts and stops								
								Mm hmm.		
	Yeah. Ehh... <i>(Long pause)</i> Umm... I'm trying to figure out why is there a zero here. 'Cause we started way up here. Where does this graph place the zero? And how does this software determine where the origin is?		Points to zero point on the axes of the graph, shows where the ball started on the graph, and then steps back while studying the graph							
								Mm hmm. Is there a question?		
	Uhh, I think so. I'm not... I don't really know how to look at this graph to determine-		Leans forward to see the graph more closely and then resizes the window of the graph to a larger size by dragging the corner							
	I mean here it says ten meters, there.		Points to the point on the x-axis labelled 10							
								So, what is this graph displaying to you?		Yeah.

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
	The y-position and the x-position.		Gesturing along the board but not pointing to any specific part of the display, they move their hand vertically while saying y-position and horizontally while saying x-position					
							Mm hmm.	
	But what I can't really see is where the x-position's zero point is. That should be there.		Points to the origin of the graph on the axes					
	But it doesn't show much more.							
			Clicks around on the region of the graph containing the data to try and figure out the reason why the origin is where it is. Hovers over the board while following the path of that the circle took from upper left to lower right (along the line on the graph)				Can you- can you say from the graph, so, where the x-position's zero is? So you're- so this graph- what does this graph represent? Like, in other words, what would you say this graph represents? 'Cause you can have velocity vs. time graph, you can have x versus time graph but this is a y versus x graph right?	
	Yeah it describes exactly where the ball has been. It shows the path of the ball.	Traces out the shape of the path of the circle with one hand						
							Mm hmm.	
							So in- in space right?	
	In space, yes.							

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
							So can you- I think you can actually see where the x zero is then.	
	Yeah when it starts rolling on the other-							
			Drags the graph window out of the way so that the rectangles can be seen.					
							Mm hmm. So.	
	When it starts rolling on that one.		Points to intersection of the two rectangles.					
							And where would you like it to be?	
				Right there.		Points to the top of the tilted rectangle		
	No. We want it on the end... there.		Drags the graph window again so that the end of the small rectangle is visible and then points to this spot on the rectangle.	No?				
				Okay.				
							So there's a way of doing that actually but you need to move your physical experiment to the left because unfortunately you cannot move the coordinate system.	
			Traces around all of the shapes on the board to select all of them				And I can- yeah and actually- yeah you can do that and then you can turn on the grid. Which will show you-	
				-where...				

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
							So if you move this graph up-	
							It's in the bottom. This grid. Yeah	Yeah... Sorry (Stands up and moves the graph out of the way of the bottom menu where the grid button resides)
								(Clicks on the grid button and then moves the graph window all the way to the left again)
							So you can actually see...	You can see.
	Ah. And this is the zero then?		Points to the where the two rectangular shapes intersect one another					
				Mm.			Yes.	
	So then we just.. take that one and move it there.		Drags all of the shapes together so that the rightmost side of the smaller rectangle is on the gridline corresponding to the zero point on the graph					
	Uhh... before we do that we should reset it though so we have the ball.		Presses the undo button until the circle comes back, moves the graph window out of the way, and then tries to select all of the shapes again					
	Uhh... what happened?		Pauses halfway through selecting and then finishes after figuring out what was going on with the grid turned on					So when you have the grid on it makes you draw on the grid too... but it looks like it worked.

Timestamp	S1			S2			R1	R2
	Talk	Gesture	Interaction with Objects	Talk	Gesture	Interaction with Objects		
			Moves all of the shapes to the left to line up the right side of the small rectangle with the grid line corresponding to the zero point on the graph again					
				This works.				
	Yeah. And from here we can...							
	Yeah.			Try it again?				
						Drags the window of the graph upward so that the data can be seen.		
	Just.. start. See what happens.					Presses the play button to start the simulation.		
			Watches the simulation run then pauses the simulation			Watches the simulation run.		
	Then we can... measure.. the x-position position and see that it went		Selects the data in the graph region and then follows the path of the circle down from upper left to lower right until they reach the point where the circle made contact with the ground (still on the graph)					
	Two point seventy-five meters	Shakes one hand for the iconic gesture of approximately						
01:09:21	With that much tilting of the ramp	Tilts the same hand down ward from and elevated wrist to show a downward tilt						

Appendix E



Transcript from the third data
set

- 1 Beth *Varför blir det så?*
Why does it happen like that?
watching the IWB
- 2 Adam *För att det är endast för två planeter så den är- den alltså du måste*
Because it's for only two planets so it's- I mean, you must
turns in his chair and looks at Beth
points his index fingers upward
(Figure 2a)
pushes himself back into his chair and looks at IWB
ju alltid ha en motkraft mot var den andra planet är.
always have a counterforce toward where the other planet is.
looks back to Beth
- 3 Beth *Ja. (1)*
Yeah.
looks at IWB
- 4 Adam *Och om den ändrar snabbare (1) så kommer väl ändå mot- alltså*
And if it changes faster well then, I mean, the count- then
rolls chair toward IWB while pointing and looking at the simulation
follows the small, circular shape of the more massive star's orbit with his index finger on the IWB
(Figure 2b, left)
då kommer det inte bildas någon motkraft. (2)
there won't be created any counterforce
looks back to Beth with his hand still over the IWB
(Figure 2b, right)
- 5 Adam *Om du och jag skulle rotera runt såhär*
If you and I were to rotate around like this
extends both hands to Beth
(Figure 3a, left)
- 6 Beth *Mhm. (1)*
Mhm.
grabs Adam's hands as he begins to roll away from her in his chair
(Figure 3a, right)
- 7 Adam *Då kan ju inte jag börja rotera snabbare än dig (1) trots att du*
Then I cannot start to rotate faster than you even though you
pulls on Beth's hands while rolling away in his chair, then rolls to the side of Beth while trying pull in the direction of his original position (Figure 3b)
releases Beth's hands
points at Beth
väger mindre än mig (1)
weigh less than me
puts hand down and looks to Beth

- 8 Beth *För att de håller i varandra på något sätt*
Because they are holding onto each other in some way.
 turns to looks at the IWB and brings hands together, interlocking her fingers (Figure 4, left) turns back to Adam and extends her hands toward him (Figure 4, right)
- 9 Adam *Exakt eftersom- alltså eftersom du- eftersom vi håller i varandra här*
Exactly, because- I mean, because you- because we hold onto each other here
 stands up out of his chair extends his hands to Beth Beth grabs Adam's hands and they lean outward from each other they fully extend their arms (Figure 5a, left) (Figure 5a, right)
- 10 Beth *Mhm. (1)*
Mhm.
 stays in position with Adam, both of them holding hands with their arms extended
- 11 Adam *Så trots att jag väger mer än dig, så kommer- kunde inte jag börja*
So even though I weigh more than you, then I will- I couldn't start to
 (overlapping) while leaving his hands in place, steps around to the side of Beth (Figure 5b, left)
 Beth: *Än mig*
than me
rotera runt här, för då kommer ju du bara ramla ut ditåt, för att
rotate around here, because then you just fall out that way, because
 stands in over rotated position points to Beth with his right hand
då finns det ingenting som håller kvar dig.
then there is nothing holding you anymore.
 points away from Beth with thumb of his right hand to the position in the dance across from her (Figure 5b, right)
- 12 Beth *Jaaaa.*
Yeaah.
 drops her hands from the dance and looks to the IWB
- Inst *I den situationen så drar ju ni i varandra med krafter. Om ni*
In this situation, then, you pull on each other with forces. If you
försöker tänka er kraftpilar eller krafter på de där objekten hur- hur
try to imagine force vectors or forces on those objects, how- how
 (overlapping)
 Adam: *Det är ju-*
It's like-
är de riktade? Och ser du någon likhet med-
they are directed? And do you see any similarities with-

- 13 Adam *Alltså, de är ju riktade mot varandra hela tiden. (1)*
I mean, they are directed toward each other all the time.
 holds his hands up to the IWB and follows both stars as they orbit, pointing his pinky fingers toward each other (Figure 6, left) repeats the motion with his index fingers pointing inward
- 14 Beth *Näe, här är de ju riktade ifrån varandra.*
No, here they are directed away from each other.
 steps up to the IWB so that Adam has to move and holds her hands over the apocenters of the orbits, pointing her index fingers out from the center (Figure 6, left)
- 15 Adam *Nä.*
No.
- 16 Beth *Nehe?*
No?
 steps back from the IWB
- 17 Adam *För du ser ju att (5)*
Because you can see *Ser du nu är de*
See, now they are
 begins to point his fingers inward on the IWB again waits for the stars to orbit until they are nearest each other, then pauses the simulation holds his hands over the two stars in the simulation and points his fingers inward (Figure 7a, left)
- riktade så. (1)*
directed like so.
 looks from the IWB to Beth
- Det är därför de går- går omlott*
That is why they go- go around
 (overlapping)
 Beth: *Jaaaaaa*
Yeaaaah
- *ohörbart**
inaudible
 looks back to the IWB and traces a small circle with his hand looks back to Beth while continuing to trace a circle (Figure 7a, right)
- 18 Beth *Och så riktas de mot varandra så jaa (1)*
And then they are directed toward each other, so yeah
 steps up to the IWB and follows the shape of the orbits while pointing her fingers toward each other steps back from the IWB as Adam presses the play button in the simulation

- 19 Adam *Så här riktas de mot varandra.* (1)
So here they are directed toward each other.
 follows the stars as they orbit in the simulation with his
 fingers pointed toward each other again as Beth watches
- 20 Beth *Mot varandra. Okej.* (4)
Toward each other. Okay.
- 21 Adam *Så (3) än deras krafter kan representeras som våra händer liksom*
So then their forces can be represented as our hands kinda.
 drops his hands and looks to Beth looks to IWB points fingers together in the air extends his hands toward Beth looks to Beth while she continues to watch the IWB
 (Figure 8a, left) (Figure 8a, right)
- 22 Beth *Mm.*
Mm.
- 23 Adam *Så för att vi två ska kunna rotera runt måste du luta dig ut*
So for the two of us to be able to rotate around, you have to lean out
 points a finger upward in the air and twirls it around in circles while looking at Beth points toward Beth
- mer än vad jag behöver*
more than I have to.
 brings his hands toward his chest to emphasize himself
- 24 Beth *Jag måste ha större bana!*
I must have a larger orbit!
 steps toward the IWB and traces the shape of the larger orbit in the simulation with her index finger while looking at Adam (Figure 8b)
- 25 Adam *Exakt.*
Exactly.
- 26 Beth *Snyggt!*
Nice!