Learning physics with Controllable Worlds

Perspectives for examining and augmenting physics students' engagement with digital learning environments

ELIAS EULER
Abstract


In this thesis I present a collection of case studies involving small groups of participants using ‘Controllable Worlds’—i.e., a particular class of physics digital learning environment (DLE) including simulations, ‘microworlds,’ and educational games that provides users with control over manipulable virtual environments. Throughout the thesis I employ and develop several perspectives for the interpretation, analysis, and instructional guidance of physics students' engagement with DLEs. While this thesis focuses in particular on participants’ use of the 2D Newtonian software Algodoo and the PhET simulation My Solar System, I also contribute to a more general scholarly discussion on student interaction and technology use in physics education. One such contribution, which relates to my development of an overarching taxonomy for learning environments, is the theoretical distinctions between ‘constrained’ and ‘less-constrained’ DLEs and between DLEs with high and low degrees of ‘semi-formality.’

The work of this thesis is largely based on five peer-reviewed publications, the content of which can be organized into three broader themes. In Theme 1, called ‘Bridging the physical and formal,’ I incorporate the perspectives of semi-formalisms, modeling, Papertian constructionism/microworlds, and informal learning to examine the ways in which less-constrained DLEs such as Algodoo can mediate between the ‘physical world’ and ‘formal world’ of physics. In Theme 2, called ‘Embodiment and the making of meaning,’ I incorporate the perspectives of multimodal social semiotics, embodied cognition, and kinesthetic/embodied learning activities in order to form a multi-perspective analytic model for examining a pair of students’ embodied interactions against the backdrop of the PhET simulation My Solar System. In Theme 3, called ‘The responsive role of the teacher,’ I incorporate the perspectives of responsive teaching, the variation theory of learning, and the grounded theory family of methods in order to explore a teaching arrangement that combines less-constrained DLEs like Algodoo with the feedback of a responsive teacher.

Especially as compared to PER work that aims to measure learning gains or conceptual mastery via assessment tools, I opt to focus instead on the mechanisms of meaning-making that occur between the ‘pre’ and ‘post.’ Thus, I am able to contribute to the theoretical picture of students’ meaning-making in digitally-rich physics learning environments. Across all of the studies in this thesis, I show how the use of technology like Controllable Worlds can lead to student behavior which is productive for physics teaching and learning in ways that may be altogether unexpected.

Keywords: Controllable Worlds, digital learning environments, modeling, semi-formalisms, microworlds, social semiotics, conversation analysis, embodied cognition, disciplinary-relevant aspects, responsive teaching, variation theory, contrast, dimensions of variation, relevance structure, creativity, grounded theory, activity types, exploration, testing, engineering

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For Desirae & Elowyn
Peer-reviewed academic work

This thesis is built on the following papers, which I refer to throughout the text by Roman numeral (i.e., Paper I, Paper II, etc.). Reprints are made with permission from the respective publishers or through the appropriate Creative Commons Attribution licenses.


Author contributions

The contributions of the respective authors for each paper are detailed below. The datasets mentioned here are clarified in Chapter 4.

Paper I: For Paper I, the development of the original idea was done by me in consultation with Bor Gregorcic. The collection of the video data (first dataset) was done by me and Bor Gregorcic together. The transcription and analysis were done by me. The illustrations and original manuscript were crafted by me. The text was improved together with Bor Gregorcic as coauthor.

Paper II: The original idea for Paper II was developed by me in consultation with Bor Gregorcic. Some of the video data (second dataset) were previously collected and then translated from Slovenian by Bor Gregorcic. The remaining data were taken from the same dataset as used in Paper I (i.e., the first dataset). The analysis of both datasets was carried out by me. The illustrations and original manuscript were crafted by me. The text was improved together with Bor Gregorcic as coauthor.

Paper III: The original idea for Paper III was developed by me in consultation with Bor Gregorcic. The video data (third dataset) were collected and initially translated from Swedish by Elmer Rådahl. The generation of the final transcripts and analysis of the data was carried out by myself. The translation of the data was subsequently checked for accuracy by Moa Eriksen and Elmer Rådahl during and after analysis. The illustrations and original manuscript were crafted by me. The text was improved together with Bor Gregorcic and Elmer Rådahl as coauthors.

Paper IV: The original idea for Paper IV was developed by me in consultation with Bor Gregorcic and Cedric Linder. The video data were taken from the same dataset as used in Papers I and II (i.e., the first dataset). The transcription and analysis were carried out by me. The illustrations and original manuscript were crafted by me. The text was improved together with Bor Gregorcic and Cedric Linder as coauthors.

Paper V: The original idea for Paper V was developed by me in consultation with Bor Gregorcic as an extension of Christopher Prytz’s master’s project. Most of the video data (fourth dataset) were collected by me alone. The remaining data were taken from the same dataset used in Papers I, II, and IV (i.e., the first dataset). The initial analysis was carried out by Christopher Prytz and was then iteratively refined by both me and Christopher Prytz. The original manuscript was crafted by me and was improved together with Bor Gregorcic and Christopher Prytz as coauthors.
Other supporting work

This thesis also draws from the following work.

**Invited Symposia**


**Conference Presentations**


**Conference Posters**


# Contents

1 Introduction ............................................................................................. 1  
1.1 My research journey ........................................................................ 2  
1.2 Research questions .......................................................................... 4  
1.3 The perspectives of this thesis ......................................................... 4  
1.4 Structure of the thesis ...................................................................... 6  
2 Existing PER work on the development and use of digital technologies ................................................................................................ 8  
2.1 Methods of review ......................................................................... 10  
2.1.1 Historical perspective: Kuhnian paradigms ........................... 11  
2.1.2 Generation of topical areas .................................................... 13  
2.1.3 Selection of articles ............................................................... 16  
2.2 The paradigms of the digital technologies work of PER .............. 17  
2.2.1 Computer-Assisted Instruction: leading up to the 1970s ....... 18  
2.2.2 Computer Constructivism: 1970s-1990s ............................... 23  
2.2.3 Computer-Supported Collaborative Learning: 1990s-now ... 28  
2.3 The topical areas of the digital technologies work of PER ........... 32  
2.4 Discussion of the digital technologies work of PER ..................... 39  
2.4.1 A pattern in the digital technologies work of PER ................ 40  
2.4.2 The future of the digital technologies work of PER and the place of my thesis in it ................................................................. 43  
3 Digital learning environments ............................................................... 47  
3.1 The anatomy of learning environments ......................................... 47  
3.2 The (flexible) facet profiles of DLEs in physics education II ....... 52  
3.3 The ‘constraints’ view of Controllable Worlds IV ......................... 54  
3.4 The DLEs I have studied ............................................................... 57  
3.4.1 Algodo II ............................................................................... 58  
3.4.2 My Solar System III .............................................................. 61  
3.4.3 Pendulum Lab.......................................................................... 62  
3.5 The contextual factors within which these DLEs were implemented in my research ................................................................. 62  
3.5.1 The interactive whiteboard II .................................................. 63  
3.5.2 Small groups of participants in isolation ............................... 63  
3.5.3 The prompts given to students.............................................. 64  
3.5.4 The researcher(s) in the room ............................................... 65


<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>A summative note on digital learning environments</td>
<td>65</td>
</tr>
<tr>
<td>4</td>
<td>Methodology</td>
<td>67</td>
</tr>
<tr>
<td>4.1</td>
<td>Case-oriented research</td>
<td>67</td>
</tr>
<tr>
<td>4.2</td>
<td>Data collection</td>
<td>70</td>
</tr>
<tr>
<td>4.2.1</td>
<td>The first dataset I &amp; II</td>
<td>70</td>
</tr>
<tr>
<td>4.2.2</td>
<td>The second dataset II</td>
<td>72</td>
</tr>
<tr>
<td>4.2.3</td>
<td>The third dataset III</td>
<td>74</td>
</tr>
<tr>
<td>4.2.4</td>
<td>The fourth dataset V</td>
<td>75</td>
</tr>
<tr>
<td>4.3</td>
<td>My general analytic approach</td>
<td>76</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Background on research on language and social interaction: the ‘embodied’ turn</td>
<td>78</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Presentation of data: multimodal transcription</td>
<td>83</td>
</tr>
<tr>
<td>4.4</td>
<td>Establishing trustworthiness and ethical integrity</td>
<td>88</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Trustworthiness</td>
<td>88</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Ethical considerations</td>
<td>94</td>
</tr>
<tr>
<td>5</td>
<td>Theme 1: Bridging the physical and formal</td>
<td>100</td>
</tr>
<tr>
<td>5.1</td>
<td>Semi-formality and modeling with DLEs (Paper I)</td>
<td>101</td>
</tr>
<tr>
<td>5.1.1</td>
<td>The perspectives taken in Paper I</td>
<td>102</td>
</tr>
<tr>
<td>5.1.2</td>
<td>Selection of data</td>
<td>103</td>
</tr>
<tr>
<td>5.1.3</td>
<td>Transcription I</td>
<td>104</td>
</tr>
<tr>
<td>5.1.4</td>
<td>What I found (analysis and discussion) I</td>
<td>104</td>
</tr>
<tr>
<td>5.2</td>
<td>Microworldiness (Paper II)</td>
<td>108</td>
</tr>
<tr>
<td>5.2.1</td>
<td>The perspective taken in Paper II</td>
<td>109</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Selection of data II</td>
<td>111</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Transcription II</td>
<td>112</td>
</tr>
<tr>
<td>5.2.4</td>
<td>What I found (analysis and discussion) II</td>
<td>112</td>
</tr>
<tr>
<td>5.3</td>
<td>Semi-formality: the mediating role of Algodoo between the physical and formal I &amp; II</td>
<td>128</td>
</tr>
<tr>
<td>6</td>
<td>Theme 2: Embodiment and the making of meaning</td>
<td>131</td>
</tr>
<tr>
<td>6.1</td>
<td>Embodiment alongside DLEs (Paper III) III</td>
<td>132</td>
</tr>
<tr>
<td>6.1.1</td>
<td>The perspectives taken in Paper III III</td>
<td>133</td>
</tr>
<tr>
<td>6.1.2</td>
<td>Selection of data III</td>
<td>139</td>
</tr>
<tr>
<td>6.1.3</td>
<td>Transcription III</td>
<td>139</td>
</tr>
<tr>
<td>6.1.4</td>
<td>Orbital motion III</td>
<td>140</td>
</tr>
<tr>
<td>6.1.5</td>
<td>The orbital periods of binary stars III</td>
<td>141</td>
</tr>
<tr>
<td>6.1.6</td>
<td>My multi-perspective analytic model III</td>
<td>143</td>
</tr>
<tr>
<td>6.1.7</td>
<td>What I found (analysis) III</td>
<td>145</td>
</tr>
<tr>
<td>6.1.8</td>
<td>Synthesis and discussion III</td>
<td>160</td>
</tr>
<tr>
<td>6.2</td>
<td>Embodiment as continuous with disciplinary physics III</td>
<td>164</td>
</tr>
<tr>
<td>7</td>
<td>Theme 3: The responsive role of the teacher</td>
<td>168</td>
</tr>
</tbody>
</table>
7.1 The use of variation theory in responsive teaching alongside DLEs (Paper IV)  ................................................................. 169
  7.1.1 The perspective used in Paper IV ...................................... 171
  7.1.2 Selection of data ............................................................... 174
  7.1.3 Transcription .................................................................... 174
  7.1.4 What I found (analysis) ..................................................... 175
  7.1.5 Synthesis and discussion of this case ............................... 189
7.2 The productivity of messing about in Algodoo (Paper V) .......... 192
  7.2.1 The perspective taken in Paper V ..................................... 193
  7.2.2 Selection of data ............................................................... 195
  7.2.3 What was found (analysis and discussion) ......................... 195
7.3 The implications of responsive teaching ................................... 200
  7.3.1 The benefits to students: going beyond conceptual mastery ..................................................................................... 200
  7.3.2 The benefits of responsive teaching for teachers .......... 201
  7.3.3 Implementing responsive teaching .................................... 202
7.4 Responsive teaching alongside a less-constrained DLE .......... 203
8 Synthesis of findings .................................................................. 206
  8.1 Answering my research questions ...................................... 206
  8.2 Looking across the five papers ............................................ 208
  8.3 On Controllable Worlds and flexible facet profiles ............. 211
    8.3.1 Defining the ‘space’ of Controllable Worlds .................... 212
    8.3.2 The quadrants of the Controllable Worlds space and moving between them ................................................................. 214
9 Contributions and implications .................................................. 221
  9.1 Theoretical contributions .................................................... 221
  9.2 Contributions to PER methods ............................................ 222
  9.3 Implications for the teaching and learning of physics .......... 223
10 Future work ........................................................................... 224
    Future directions stemming from my work .......................... 224
    Frontiers of focus for the digital technologies work of PER ...... 225
Sammanfattning på svenska .......................................................... 229
Acknowledgements ........................................................................ 232
References .................................................................................... 234
# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
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<tr>
<td>AR</td>
<td>Augmented reality</td>
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<tr>
<td>BBN</td>
<td>Bolt, Beranek, and Newman</td>
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<td>CAI</td>
<td>Computer-Assisted Instruction</td>
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<td>CC</td>
<td>Computer Constructivism</td>
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<tr>
<td>CSCL</td>
<td>Computer-Supported Collaborative Learning</td>
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<tr>
<td>CUPLE</td>
<td>Comprehensive Unified Physics Learning Environment</td>
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<tr>
<td>DBER</td>
<td>Discipline-Based Education Research</td>
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<td>DLE</td>
<td>Digital learning environment</td>
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<td>DoV</td>
<td>Dimension of variation</td>
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<td>DRA</td>
<td>Disciplinary relevant aspect</td>
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<td>ELA</td>
<td>Embodied learning activity</td>
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<tr>
<td>FCI</td>
<td>Force Concept Inventory</td>
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<tr>
<td>FMCE</td>
<td>Force and Motion Concept Evaluation</td>
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<tr>
<td>GIREP</td>
<td>Groupe International de Recherche sur l’Enseignement de la Physique</td>
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<tr>
<td>HCIs</td>
<td>Human Computer Interfaces</td>
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<td>ICPE</td>
<td>International Commission on Physics Education</td>
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<td>IUPAP</td>
<td>International Union of Pure and Applied Physics</td>
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<tr>
<td>KLA</td>
<td>Kinesthetic learning activity</td>
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<tr>
<td>LMS</td>
<td>Learning Management System</td>
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<td>LSI</td>
<td>Language and social interaction</td>
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<tr>
<td>MR</td>
<td>Mixed reality</td>
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<td>MUPPET</td>
<td>Maryland Project in Physics and Education Technology</td>
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<tr>
<td>NRC</td>
<td>National (American) Research Council</td>
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<tr>
<td>OEEC</td>
<td>Organisation for European Economic Co-operation</td>
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<tr>
<td>PBL</td>
<td>Problem-based learning</td>
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<td>PER</td>
<td>Physics Education Research</td>
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<tr>
<td>PLATO</td>
<td>Programmed Logic for Automatic Teaching Operations</td>
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<td>RQ</td>
<td>Research question</td>
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<tr>
<td>SFL</td>
<td>Systemic functional linguistics</td>
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<td>VR</td>
<td>Virtual reality</td>
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</tbody>
</table>
The glossary below details my specific use of a selection of important terms that feature throughout my thesis. Terms that appear in **bold** were coined by me (or redefined by me) for the purposes of my research.

<table>
<thead>
<tr>
<th><strong>black box simulations</strong></th>
<th><strong>Controllable Worlds</strong> that function as <strong>constrained</strong> and with a low degree of <strong>semi-formality</strong></th>
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</thead>
<tbody>
<tr>
<td><strong>case-oriented research</strong></td>
<td>research focused in-depth on single cases (i.e., lone instances); “[assumes] that (1) social actions are guided by the meanings that people are making of their local environments and that (2) reality is subjectively constructed” (Robertson et al., 2018, p. 11)</td>
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<tr>
<td><strong>Computer-Assisted Instruction</strong></td>
<td>the first paradigm I identify in the PER work on the use and development of digital technologies, stretching up until sometime in the early 1970s; typified by the belief that technology should act as an efficient teacher/tutor, delivering content and determining if students have learned what is delivered (Koschmann, 1996)</td>
</tr>
<tr>
<td><strong>Computer Constructivism</strong></td>
<td>the second paradigm I identify in the PER work on the use and development of digital technologies, stretching from the 1970s to the 1990s; typified by the belief that technology should act as a systematic environment (allowing students to build worlds and calculate), and/or to act as a sensor for probing the physical world</td>
</tr>
<tr>
<td><strong>Computer-Supported Collaborative Learning</strong></td>
<td>the third paradigm I identify in the PER work on the use and development of digital technologies, which emerged in the 1990s; typified by the belief that technology should function as facilitator of the interpersonal act of learning among students and teachers (Koschmann, 1996)</td>
</tr>
<tr>
<td><strong>constraints (criterion)</strong></td>
<td>the extent to which the set of dimensions of variation made available by a digital learning environment is restricted</td>
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<tr>
<td><strong>construction kits (facet)</strong></td>
<td>the facet of learning environments that, similar to symbol pads, act as the locus of construction and manipulation, but do so for a “fund of prefabricated parts and processes” (Perkins, 1991, p. 19)—e.g., electronics labs, ‘Maker Spaces,’ programming languages, etc.</td>
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contrast in variation theory, the principle that says that, in order to maximize the possibility of learning about an aspect, one should experience that aspect vary against a fixed background (Fredlund, Airey, & Linder, 2015; Marton & Booth, 1997; Marton & Pang, 2013)

**Controllable Worlds** digital (educational) technologies that provide users with control over manipulable virtual environments (adapted from Bork, 1981)

digital learning environments technologically self-contained learning settings (typically software) that are situated within broader learning environments

dimension of variation in variation theory, an aspect across which a range of values can be experienced (Fredlund, 2015; Häggström, 2008; Marton & Booth, 1997; Maunula, 2017); may be ‘opened up’ (i.e., experienced for the first time) or ‘involved’ (i.e., selectively included during problem solving and/or group interaction)

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

embodied imagery ‘meso-scale’ cognitive units—neither ‘microscopic,’ irreducible building blocks (c.f., diSessa 1988) nor ‘macroscopic’ conceptions—that serve as the source domain of the students’ metaphoric language as grounded in their embodied experiences of the material world

embodied learning activities activities where a teacher incorporates students’ bodies, or parts of their bodies, as metaphorical substitutes for physical entities in a role-playing of physical phenomena (Scherr et al., 2012)

enacted relevance structure the relevance structures implied by students’ observed choice of dimensions of variation in a given interaction

facet profile the particular combination of the facets in a learning environment (i.e., information banks, symbol pads, construction kits, phenomenaria, task managers, and interactional spaces), which implies tacit pedagogical values (Perkins, 1991)

information banks (facet) the facet of learning environments that “[serve as [sources] of explicit information about topics” (Perkins, 1991, p. 18); the “Repositories of Ideas” (Hooke, 1705) in a given learning environment—e.g., teachers, textbooks, worksheets, Wikipedia, etc.

interactional spaces (facet) the facet of learning environments comprising the physical
and digital ‘chambers’ that make possible the social interactions of students and teachers—e.g., lecture halls, labs, learning management systems, social media, etc.

**kinesthetic learning activities**

“[activities] which physically engage students in the learning process” (Begel et al. 2004, p. 1), including activities such as laboratory work or demonstrations where students might interact with physical apparatus, but also those activities where students might use their bodies as sensors for physical interactions.

**microworlds**

*Controllable Worlds* that function as **less-constrained** and with a high degree of **semi-formality**.

**multimodality**

the notion that humans communicate in a variety of ways (Jewitt, Bezemer, & O’Halloran, 2016), that is, not only with written and spoken language but also with gestures, gaze, manipulation of objects, static and dynamic images, haptic-touch, body posture, etc.

**open-ended prompts**

prompts designed to encourage “activities in which students have greater autonomy in what and how physical phenomena are investigated, rather than simply following instructions” (Wilcox & Lewandowski, 2016, p. 1).

**paradigms**

in the history of science, new schools of scientific thought that are both “sufficiently unprecedented to attract an enduring group of adherents from competing modes of scientific activity” and also “sufficiently open-ended to leave all sorts of problems for the redefined group of practitioners to resolve” (Kuhn, 1970, p. 10).

**perspectives**

in this thesis, theoretical frameworks for the interpretation, analysis, and instructional guidance of physics students’ engagement with **digital learning environments**

**phenomenaria (facet)**

the facet of learning environments designed “for the specific purpose of presenting phenomena and making them accessible to scrutiny and manipulation” (Perkins 1991, p. 19)—e.g., demonstration apparatus, simulation software, etc.

**phenomenological primitives**

(i.e., ‘p-prims’) infinitesimal cognitive units formed through “simple abstractions from common experiences that are taken as relatively primitive in the sense that they generally need no explanation” (diSessa, 1988, p. 52)—e.g., *Ohm’s Law* p-prim, *Force as mover* p-prim, etc.

**programming environments**

when used to create manipulable virtual environments that functionally resemble *Controllable Worlds*, **digital learning environments** that function as **less-constrained** and with low degree of **semi-formality**.
recurrence-oriented research  research focused on re-occurring phenomena (i.e., many re-peatable instances); “is predicated on the assumptions that (1) human behavior is guided by predictable relationships between variables and that (2) real phenomena are reproducible” (Robertson et al., 2018, p. 9)

relevance structure in variation theory, that which is deemed to be needed (by a specific person) to appropriately deal with a situation at hand (Marton & Booth, 1997)

semi-formalisms digital access points to the formal ideas of physics that can be strongly related to students’ intuition (diSessa, 1988)

semi-formality (criterion) the extent to which a digital learning environment functionally mediates between the ‘physical world’ and ‘formal world’ of physics by providing a physically-intuitive space within which students can create with the formal materials of the discipline of physics

semiotic resources specific instances of externalized meaning-making (Airey & Linder, 2017)—e.g., a specific disciplinary/non-disciplinary graph, a diagram, a figure, an equation, etc.; but also, a specific disciplinary/non-disciplinary gesture, meaningful body position, instance of haptic-touch, ‘chunk’ of speech, etc.

semiotic systems (also, ‘modes’) the classes of semiotic resources used in externalized meaning-making—e.g., talk, gesture, equations, graphs, haptic-touch, manipulation of the environment, etc. (Volkwyn et al., 2019)

simulations Controllable Worlds that function as constrained and with a high degree of semi-formality

symbol pads (facet) the facet of learning environments designed for the “construction and manipulation of symbols” (Perkins, 1991, p. 18)—e.g., notebooks, tablets, blackboards, interactive whiteboards, etc.

task managers (facet) the facet of learning environments that “set tasks to be undertaken in the course of learning, guide, and sometimes help with the execution of those tasks” (Perkins, 1991, p. 19)—e.g., tutorials, intelligent tutors, etc.
Preface

The doctoral thesis you hold now is the culmination of the last four years of my physics education research (PER) work investigating how study participants made use of certain digital learning environments (DLEs) when working in small-groups. In crafting this text, I have incorporated the work from five peer-reviewed papers (labelled Papers I-V) as well as my licentiate thesis—*Perspectives on the role of digital tools in students’ open-ended physics inquiry* (Euler, 2019). The latter was completed and publicly defended at roughly the halfway mark of my doctoral candidacy in May of 2019.

At Uppsala University (and Swedish/Finnish universities at large), a licentiate degree is formally recognized as being equivalent to half of a doctoral degree (Uppsala University, 2020). My licentiate thesis was based around the three papers that I had published up until that point: Papers I, II, and III. In Sweden, the theses that accompany licentiate/doctoral degrees in the natural sciences typically consist of a collection of three or more published papers preceded by a chaptered ‘kappa.’ The kappa is understood to be a ‘comprehensive summary’ of the papers. Though on the whole uncommon in much of the natural sciences, licentiate and doctoral candidates in the Division of Physics Education Research at Uppsala University (where I have undertaken my doctoral work) often write theses that are stand-alone texts, incorporating the previously-published work—i.e., both the published papers and the defended licentiate thesis—into a single, new dissertation. Such theses blend the format of a kappa and a standalone monograph. The text you are reading now is an example of such a thesis.

Being that this doctoral thesis is built up from five papers and expands upon the licentiate thesis I defended a year and a half prior, it is worthwhile here for me to discuss the extent to which I have incorporated previously-published material. The topic of plagiarism—and, more precisely, the less-pernicious act of ‘textual recycling’ (Bruton, 2014) that I employ throughout this thesis—is certainly one worth addressing. Therefore, I have opted for complete transparency here and throughout the remainder of this thesis with regards to the reuse of my own published work. On frequent occasion throughout sections of this thesis, I make use of portions of text which originally appeared in Papers I-V. This has occasionally meant that sections of my papers are reproduced verbatim, but more often it has meant that the text from the papers has been edited and adapted to better cohere all together in this doctoral thesis. At each of the instances where I use previously published work from
Papers I-V, I denote the original paper with a roman numeral superscript (e.g., a section which includes text from Paper II is labelled as ‘Section title II’). My reason for using text from my published papers—which to some academic minds might appear as an example of unscrupulous ‘self-plagiarism’—is to quite literally build a comprehensive story from all five of these papers. Including parts of the papers in the body of the thesis has allowed me to maintain a continuous narrative, linking the parts of my doctoral work into a coherent whole. It also improves the reading experience by not asking the reader to jump between the thesis and the attached papers included at the end. With regards to the use of text from my May 2019 licentiate thesis, I have not used the same system of roman numerals used to refer to reused work from the papers. Instead, I have provided a detailed overview of the work I have done in transforming the text of my licentiate thesis into the final text of my doctoral thesis in Appendix A.

For stylistic reasons in the text of my thesis, I have opted to use the singular pronoun ‘I’ rather than the collective pronoun ‘we’ in order to improve the flow between sections and to reduce ambiguity between instances when the ‘we’s’ would have been referring to different collections of collaborators. Nonetheless, each paper was crafted out of a collaborative effort with the respective coauthors (see the ‘Author contributions’ section for details) and I entreat the reader to be reminded of my colleagues’ efforts when superscripts appear throughout the text.

This thesis is my stitching together a patchwork of original material and previously-crafted material in an effort to synthesize a new, single narrative thread representing the entirety of my doctoral work. The result is a doctoral thesis that develops theoretical and practical perspectives for physics educators and physics education researchers interested in how physics students engage with digital learning environments. I hope you enjoy reading it as much as I have enjoyed researching and writing it.

Elias Euler

2020
1 Introduction

There is currently little by way of reported physics education research (PER) examining how digital technologies are used by physics students on a moment-to-moment basis and how the experiences of using these technologies might manifest as valuable physics learning. Instead, a significant portion of the PER work related to the development and use of digital technologies has tended to bias itself toward the pursuit of technological innovations and, as a result, has tended to overpromise grand transformations in teaching practice through newer and ‘shinier’ digital tools. This has likely caused a mounting degree of apathy among a subset of the physics education community toward the rarely-realized outcomes that ‘techno-enthusiasts’ involved in the digital technologies work of PER have repeatedly promised (see Chapter 2).

In the spirit of these issues surrounding digital tools in PER, this thesis comprises my exploration of the ways in which, through a series of case studies, physics students can be observed to utilize a particular type of digital learning environment, namely what I have come to call Controllable Worlds. Throughout this thesis I take digital learning environments (DLEs) to mean technologically self-contained learning settings (typically software) that are situated within broader learning environments. Controllable Worlds are a particular class of DLE—including simulations, so-called ‘microworlds,’ and educational games—that provides users with control over manipulable virtual environments (adapted from Bork, 1981). In particular, this thesis centers on my work to develop and implement a set of perspectives—i.e., theoretical frameworks for the interpretation, analysis, and instructional guidance of physics students’ engagement with DLEs—within case studies of small groups of participants using non-cutting-edge Controllable Worlds. My hope is that the perspectives featured in this thesis provide the interested education researcher with frameworks and methods to examine how students make use of technologies, that the perspectives provide the physics teacher with insights into how and why they might use Controllable Worlds in their practice, and that the perspectives provide the designers of future education technologies with a set of research-informed justifications for their design decisions that go beyond a never-ending gold rush for technological innovation.
1.1 My research journey

From the start, I did not set out in my doctoral work to address a specific problem. Rather, my intention was to use a collection of evolving case studies to explore physics students’ use of Controllable Worlds as it took place. I began my research journey investigating how pairs of participants might make use of a relatively under-researched physics software, *Algodoo* (Algoryx Simulation AB, 2011)—which my main supervisor had examined in conjunction with a project on the affordances of interactive whiteboards prior to my arrival at Uppsala University (Gregorcic, 2015a, 2015b; Gregorcic, Etkina, et al., 2017; Gregorcic, Planinsic, et al., 2017). I was especially interested early on in studying how *Algodoo* might be observed to make the mathematical formalisms of physics more readily relatable to the intuitions of physics students. At the same time, I envisaged the theoretical and methodological contributions of my work as being not only useful for future PER work but also a source of knowledge capable of generating recommendations for physics teachers using or intending to use DLEs in their teaching.

Subsequently, my research examining the structure and function of *Algodoo* led to a data collection session focused on comparing this DLE against the foil of another kind of DLE more commonly used within the physics education community—namely a PhET simulation, *My Solar System* (PhET Interactive Simulations, 2018). I would later come to characterize the former DLE as a concrete example of a ‘less-constrained’ Controllable World, with the latter DLE being an example of a ‘constrained’ Controllable World. Although the initial research intent with the ‘constrained’ *My Solar System* was to directly compare how physics students use it in comparison to *Algodoo*, a particularly rich case of two participants engaging in an embodied dance around the PhET simulation was collected that ultimately warranted direct attention. I had the realization that, in my data, the participants were not only meaningfully interacting with the DLEs in interesting ways, but also with each other within their small group work. I thereby began focusing less in my research on the specific design aspects of the digital technologies and more on the bodily interactions of physics students around the Controllable Worlds class of DLEs. My attention turned to developing analytic perspectives for interpreting the ways in which participants’ digitally-backdropped meaning-making with one another could be judged to be continuous with disciplinary physics—i.e., such that “there exists a trajectory over which [those interactions could] become a scientific concept” (Goodhew et al., 2019, p. 1).

Finally, motivated again from the richness of some of my case study data, it became apparent to me that, throughout my collected data, a third factor was also playing a key role in the participants’ use of DLEs. I found that the researchers present during data collection—acting intuitively as quasi physics teachers—were responding to the participants’ activity in interestingly fruitful
ways, especially when the participants were engaging with the ‘less-constrained’ Algodoo. I shifted my focus yet again, this time toward developing perspectives for responsive teachers to interpret and guide physics students use of less-constrained DLEs such as Algodoo.

Such was the progression of my doctoral work. I was propelled through my research by a cascading series of case studies, first starting from my supervisor’s experience with a specific digital tool and thereafter building to new interests uncovered during investigations into the case studied prior. Looking across my work, my research can be organized into a single scholarly tableau of an ecosystem of relationships between students, DLEs, the physical world, and teachers. More specifically, I can organize my work around three themes relating to three broad ways in which I have explored this ecosystem. The first of these themes, explored in Papers I and II, involves my research on how DLEs like Algodoo can serve a mediating role between the physical intuitions of students and the formal mathematical tools of disciplinary physics. I call this theme ‘Bridging the physical and formal.’ The second theme, which I call ‘Embodiment and the making of meaning,’ involves my research in Paper III on how physics students can engage in embodied interactions with one another in the context of a digitally-rich learning environment. The third and final theme, explored in Papers IV and V, involves my research on how physics teachers can act responsively to guide students’ use of DLEs. I call this last theme ‘The responsive role of the teacher’ (Figure 1).

Figure 1. The relational ecosystem explored in this thesis involving a digital learning environment, groups of students, the physical world, and teachers. To the right, I summarize how the three themes of my work explore certain relationships within this ecosystem.
1.2 Research questions

As detailed above, the work presented in my thesis was emergent. I did not start out with a formal problem and consequent research questions. It began with an initial interest in an under-researched software (Algodoo) and grew from the outcomes and observations made as I progressed along my research journey. Viewing this emergent progression of my research in terms of the three themes does, however, allow me to collectively capture the essence of my doctoral work in the following three research questions:

**RQ 1.** As a concrete example of a less-constrained digital learning environment, how can Algodoo be observed to act as a mediator for students between the ‘physical world’ and the ‘formal world’ of physics?

**RQ 2.** How can students working in a digitally-rich environment be observed to make use of embodied, non-disciplinary meaning-making resources to reason in ways that are continuous with disciplinary-relevant aspects of a given physics task?

**RQ 3.** How can teachers effectively interpret and guide students’ use of the less-constrained digital learning environment Algodoo such that those students engage in productive activities for their learning of physics?

Each of these three research questions corresponds, respectively, to the three themes shown in Figure 1. I have answered each of these research questions, with the exception of a portion of my answer to RQ 3 (see Section 7.2), from individual case studies involving a fine-grained analysis of participants’ small group interactions around Controllable Worlds. Furthermore, each research question has entailed the development of sets of different perspectives—again, by which I mean, theoretical frameworks for the interpretation, analysis, and instructional guidance of physics students’ engagement with DLEs.

1.3 The perspectives of this thesis

In the course of answering the above research questions, this thesis presents and develops a set of perspectives for attending to physics students’ use of DLEs. Contrary to what might be typical in other education research doctoral theses, I have not persisted with any one perspective across the five papers of my thesis work. Instead, I have consistently sought to develop a range of perspectives—befitting the emergent set of noteworthy cases I have collected and analyzed—that may be useful for physics education researchers, physics
teachers, and the designers of physics educational technologies alike (see Table 1).

### Table 1. The perspectives I apply in this thesis, organized by theme. Those perspectives in bold are ones that are dealt with multiple times due to their significance for PER and my thesis in particular.

<table>
<thead>
<tr>
<th>The themes of this thesis</th>
<th>The perspectives I apply and develop</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Theme 1</strong></td>
<td>Semi-formalisms</td>
</tr>
<tr>
<td>Bridging the physical and the formal</td>
<td>Modeling</td>
</tr>
<tr>
<td></td>
<td><strong>Constructionism/microworlds</strong></td>
</tr>
<tr>
<td></td>
<td>‘Informal learning’</td>
</tr>
<tr>
<td><strong>Theme 2</strong></td>
<td><strong>Multimodal social semiotics</strong></td>
</tr>
<tr>
<td>Embodiment and the making of meaning</td>
<td>Embodied cognition/conceptual metaphor</td>
</tr>
<tr>
<td></td>
<td>Kinesthetic/embodied learning activities</td>
</tr>
<tr>
<td><strong>Theme 3</strong></td>
<td>Responsive teaching</td>
</tr>
<tr>
<td>The responsive role of the teacher</td>
<td>Variation theory of learning</td>
</tr>
<tr>
<td></td>
<td>The grounded theory family of methods</td>
</tr>
</tbody>
</table>

Since my thesis comprises an exploration of perspectives paper by paper, I will present the details of these perspectives adjacent to the analyses in which they feature—i.e., the perspectives of **Theme 1** appear alongside my discussion of Papers I and II in Chapter 5, those of **Theme 2** appear alongside my discussion of Paper III in Chapter 6, and those of **Theme 3** appear alongside my discussion of Papers IV and V in Chapter 7. The exceptions to this pattern are the perspectives that appear **bolded** in Table 1. These two perspectives are not only discussed alongside the analyses in which they appear, but are also discussed in sections preceding my discussion of the specific papers due to their significance for PER and the particular analytic approach of my thesis. Specifically, the first of these—Papert’s (1980a) perspective around constructionism/microworlds—is discussed in Chapter 2, where it features as an influential perspective in the historical progression of the use and development of digital technologies in PER (see my discussion of ‘Computer Constructivism’ in Section 2.2.2). Likewise, multimodal social semiotics is dealt with explicitly in Chapter 4 regarding to the ‘embodied turn’ (Nevile, 2015) within research on language and social interaction that informs my general analytic approach (see Section 4.3.1).

There are two other perspectives that feature in this thesis beyond those listed in Table 1. First, across Papers I-IV, I have employed a general analytic approach inspired by the perspective of multimodal conversation analysis. My use of this perspective—detailed in Section 4.3—stems from my interest to analyze how Controllable Worlds are used by physics students on a moment-to-moment basis. Second, I have adapted and developed a general taxonomy for learning environments from Perkins (1991)—presented in Chapter 3—which allows me to better synthesize some of the findings of the five papers within the context of
this thesis (realized in Chapter 8). However, though this taxonomy was adapted for the purposes of this thesis, it also results in a practically useful system for physics educators interested in the implementations of digital technologies (especially Controllable Worlds) in physics learning environments.

1.4 Structure of the thesis

This thesis is structured as follows. In Chapter 2, I present a review of the relevant PER literature involving the use and development of digital technologies. I accomplish this both through a Kuhnian analysis of the historical progression of the PER community’s attention to digital technologies since the 1950s and also through the creation of seven topical areas for the existing digital technologies research within PER. At the end of Chapter 2, after my review of the relevant literature from the past and present of PER, I then reflect on some of the common pitfalls that are endemic to this area of research and to illustrate how the research of this thesis contributes to a heretofore under-explored corner of the PER work relating to digital technologies.

In Chapter 3, I develop a new taxonomy for the analysis and discussion of DLEs in PER based on Perkins’ (1991) categorization scheme for learning environments. In doing so, I present an overarching theoretical perspective for this thesis that can be used to account for the situational dependency of DLEs as they function for students within specific contexts. I then provide details about the specific DLEs that I have explored in my thesis work—namely, the Controllable Worlds of Algodoo and the simulation software My Solar System—and the contextual factors within which I implemented these DLEs during my research.

In Chapter 4, I discuss the interpretivist, case-oriented methodology and methods used across the first four papers that constitute this thesis (with my discussion of the methods used in Paper V coming later in Chapter 7). I detail my general, multimodal analytic approach as inspired by conversation analysis, with a relevant aside on the recent shift toward students’ embodied meaning-making in research involving language and social interaction. This chapter is also where I discuss the topic of trustworthiness and research ethics. It is worth noting that, since my research was emergent from a cascading series of case studies, the second, third, and fourth chapters of this thesis play a somewhat different role than what is typically seen in the ‘Literature Review,’ ‘Theoretical Framework,’ and ‘Methodology’ chapters of PER theses. My aim with these chapters is not to reveal a ‘missing knowledge part’ that I set out to rectify, but to establish the need for the research journey that I followed and why it was emergent in character. At the same time, I intend these chapters to provide a solid foundation, not only for the formulation of research questions, but also for the rigor and quality of the approaches that were used to answer these research questions.
Chapters 5, 6, and 7 are dedicated to the three themes of the thesis respectively. The structures of these three chapters resemble one another, involving first a discussion of the respectively relevant perspectives, then moving to a discussion of selection of data and transcription, before finally a presentation of the analyses themselves. I present these perspectives adjacent to the particular case studies in which they were utilized for two main reasons: (1) to account for the emergent nature and evolution of my work and (2) to improve readability of the thesis by avoiding a lengthy and seemingly eclectic section where all the perspectives are presented together but separated from the analyses. To reiterate, Chapter 5 includes the case studies originally presented in Papers I and II, as analyzed from the perspectives of semi-formalisms, modeling, and constructionism/microworlds. Chapter 6 utilizes the perspectives of multimodal social semiotics, embodied cognition, and kinesthetic/embodied learning activities in conjunction with the case study from Paper III. Finally, Chapter 7 features the work from Papers IV and V, wherein I utilized the perspectives of responsive teaching, the variation theory of learning, and the grounded theory family of methods.

In Chapter 8, I summarize my answers to my three research questions and synthesize the results from the previous three chapters. I also return to the taxonomy introduced in Chapter 3 in order to illustrate how the findings of this thesis can inform the categorization and implementation of Controllable Worlds in physics teaching and learning.

In Chapter 9, I synopsize contributions of this thesis in bullet points for three larger headings: (1) theoretical contributions, (2) contributions to PER methods, and (3) implications for the teaching and learning of physics.

Finally, in Chapter 10, I discuss potential areas of future work that build on the research of the preceding chapters. These include specific recommendations for how future PER work might build on each of three themes of this thesis as well as two ‘frontiers’ of focus for the future research around digital technologies in physics education. Following this final chapter, there is a Swedish summary (sammanfattning). The back matter of this thesis includes appendices as well as copies of the five published papers that comprise the peer-reviewed research of this thesis. Appendix A is an overview of the work done in transforming the text of my licentiate thesis into the final text of this doctoral thesis. Appendices B-E are the consent forms used during collection of my four datasets. Appendix F and G include two sample transcripts generated from my video data.
2 Existing PER work on the development and use of digital technologies

To begin, it is worthwhile for me to first situate and motivate the work of this thesis by way of a thorough review of the existing literature on the development and use of digital technologies use in the scholarly community of PER—referred to hereafter as the ‘digital technologies work of PER.’ The primary aim of this chapter is to provide the background and context within which I can position the research of my thesis. However, to the best of my knowledge, a contemporary review of the digital technologies work of PER has not yet been completed (in comparable detail to other PER reviews such as Beichner, 2009; Cummings, 2011; Docktor & Mestre, 2014; McDermott & Redish, 1999; Meltzer & Thornton, 2012; Russ & Odden, 2018). Thus, in reviewing the literature on the digital technologies work of PER here, I also aim to provide a practical summary and synthesis of a body of academic work that could be of use in the broader scholarship on educational technology (especially within, but not limited to, the subject of physics).

The majority of this chapter is devoted to cataloging, historically contextualizing, and categorizing the research efforts of others. However, in the interest of situating the work of my thesis, I also reflect at the end of this chapter on the relative novelty and necessity of my own work within the broader landscape of the digital technologies work of PER. In this way, I am able to show how the type of interpretivist, case-driven research on students’ collaborative use of non-cutting-edge technologies that I have conducted in this thesis begins to reveal a crucial corner of digital technologies work in PER that has remained heretofore relatively unexplored.

My review of the relevant literature for this thesis has two main parts. First, I present the developmental history of the digital technologies work of PER through a lens of Kuhnian paradigms (Section 2.2). This historical portion of my literature review is intended to provide a chronological viewpoint for this specific subset of PER, revealing the ways in which technology-interested PER scholars over the last 60 years have aligned and diverged from one another in their philosophies around education and the role to be played by digital tools. Second, I present a ‘map’ of the existing digital technologies work of PER in terms of seven topical areas (Section 2.3). This second part of my literature review is intended to provide an overview of the current research
dealing with the development and use of digital technologies in physics education so as to depict the diversity of technologies typically researched in physics teaching and learning contexts.

Before I present either of these literature review parts, I first discuss the methods I used in crafting them (Section 2.1). Subsequently, after having presented the history and topical areas of the digital technologies work of PER in Sections 2.2 and 2.3, I discuss the accuracy of my methods and present some of the patterns and pitfalls found across the preceding two sections (Section 2.4). In the final part of this chapter, I finally situate my research within the broader context of the much-needed considerations of the future digital technologies work of PER.

The interrelated evolutions of digital technology and PER

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 in 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 universities. To the extent that this is the case, PER can be considered a specific instantiation of discipline-based education research (DBER). The label of DBER is generally applied to those research enterprises that “[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). ¹

Mentioning ‘digital technology’ can tend to imply a contemporaneousness with our current culture. That is to say, perhaps within the present atmosphere of tech-infused life, digital technology appears to be more of a modern-day zeitgeist than a mid-twentieth-century one. From this perspective, it is reasonable to assume that the study of digital technology in a field such as PER might be 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. For instance, 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 I will discuss in Section 2.1, what many consider to be ‘modern PER’ came about in the 1970s as well. In reality, even from the earliest stirrings of PER seen in the science curriculum development projects of the 1950s and 1960s, there has been a consistent—albeit minority—focus on

¹ Although 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 imply, by association, that I condone all of the recommendations for DBER that the NRC produced in the cited report.
the role of digital technology in PER. Ironically for those thinking that today’s abundance of revolutionary technologies must make the current moment a historical hotbed for research involving tech, the reality is that a significant proportion of the PER focusing on digital technology is already decades old at the time of writing.

I contend in this chapter that the developmental histories of digital technology and PER are inextricably linked. Much of the early PER work tasked itself with revolutionizing the physics classroom with computers and these efforts have remained woven into the identity of PER work to this day. Likewise, many of the professionals working to advance the capabilities of computing technology across the last 60 years have done so with an effort toward innovating physics education.

An important qualification to note before delving into the details of this literature review is that the overwhelming majority of PER has occurred and continues to occur in universities within the United States. Due to the relative scarcity of non-American PER work—and perhaps because of the critical mass of the American PER community unto itself—most reviews of the field have been made by American authors who fail to mention much of anything about the PER efforts outside the U.S. This tends to portray PER community as an exclusively American one. However, there is (and throughout all of PER’s history, has been) non-American PER work that is worth recognizing. Similarly, while a large portion of PER is done in physics departments at the university level, a growing body of research on physics education is being conducted 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 typical with physics education researchers. This chapter lays out the development of PER as field, especially as it relates to the use and development of digital technologies in physics teaching and learning contexts. In an attempt to go beyond the American-centric patterns of past PER reviews, I have endeavored to include some relevant non-American PER work and science education work. Admittedly, what I have included as relevant is a matter of my judgement—and a more thorough review of non-American PER remains overdue—but I hope that in highlighting some oft-overlooked, non-American literature sources, I can at least partially avoid the pattern of exclusion which has left so much important PER work unrecognized in reviews of this type.

2.1 Methods of review

Before presenting the history and topical areas of the digital technologies work of PER, I will first discuss the methods I have used in compiling this literature
review. For the historical portion of this chapter, I have chosen to adapt a review conducted by Koschmann (1996) on the non-subject-specific progression of instructional technology. As I explain below, this has meant that I make use of the Kuhnian notion of ‘paradigm shifts’ in the advancement of scientific history (Kuhn, 1970). Subsequently, for the portion of this chapter where I present the topical areas of digital technology work in PER, I have examined a variety of categorization schemes for technology employed by education scholars since the 1960s and synthesized/manufactured a new scheme befitting modern day PER.

2.1.1 Historical perspective: Kuhnian paradigms

In addressing the histories of digital technology and PER, I take inspiration from Koschmann’s (1996) review of general instructional technology. Koschmann (1996) chooses to cast the development of instructional technology as a series of revolutions through scientific paradigms, as an application of Thomas Kuhn’s (1970) work on the nature of scientific revolutions. In this chapter, I have retained Koschmann’s use of Kuhnian paradigms. However, I have done so with an added layer of skepticism for the appropriateness of paradigms and revolutions as labels for characterizing for this thread of history on which I have focused. I discuss some of the fraught nature of Kuhnian analyses later in this section, and then return to the appropriateness of paradigms for this specific subset of PER in Section 2.4. For now, it is worthwhile here for me to define the terminology of Kuhnian paradigms and lay out Kuhn’s (1970) perspective on the history of science.

In his widely-influential work *The Structure of Scientific Revolutions* (1970), Thomas Kuhn presented a perspective for viewing the history of scientific progress in terms of paradigm shifts. Kuhn defines scientific paradigms as new schools of scientific thought that are both “sufficiently unprecedented to attract an enduring group of adherents from competing modes of scientific activity” and also “sufficiently open-ended to leave all sorts of problems for the redefined group of practitioners to resolve” (1970, p. 10). Examples of scientific paradigms in physics include the Newtonian paradigm of mechanics and the Franklinian paradigm of electricity. For Kuhn, the emergence of a new, coherent paradigm within a discipline constitutes a revolution in said discipline. Using Kuhn, Koschmann explains that a paradigm can be seen as a revolutionary departure from the research which preceded it, marking a fracture in the community researchers around issues of “terminology, conceptual frameworks, and views on what constitutes the legitimate questions of science” (1996, p. 2).

It is important to note that, in the Kuhnian view of paradigms—at least in the manner Koschmann implements it—the emergence of each new paradigm does not necessarily signal the death of the old one. For example, Koschmann (1996) describes four key paradigms in instructional technology research,
namely (1) Computer-Assisted Instruction, (2) Intelligent Tutoring Systems, (3) Logo-as-Latin, and (4) Computer-Supported Collaborative Learning. In this characterization, the emergence of the second, Intelligent Tutoring Systems, paradigm does not mean that the Computer-Assisted Instruction paradigm ceased to garner any attention from researchers whatsoever. Instead, each paradigmatic shift marks the emergence of a new branch of instructional technology work which runs parallel to the existing branches.

As previously stated, I have chosen in this chapter to follow Koschmann’s utilization of the terminology of paradigmatic revolutions to describe the historical advancement of digital technologies in PER. However, a candid utilization of Kuhn’s historiographical perspective entails addressing the fraught backdrop surrounding Kuhnian paradigms. I will do so here before reflecting on why the term is nonetheless useful for my discussion of digital technologies in this chapter.

The divisive nature of Kuhnian paradigms stems from a few factors. First, the charismatic explanatory power of Kuhn’s perspective has meant that many mundane instances of change within a field or discipline often get mislabeled as grand ‘paradigm shifts’ by overeager advocates of innovation (see, for instance, the discussion in Harvey, 1982). As Kuhn decries himself, “part of the reason for [the success of the paradigm perspective] is, I regretfully conclude, that it can be too nearly all things to all people” (Kuhn, 1974, p. 459). Beyond this, and perhaps even more damming in a discussion on the application of Kuhnian historiography, is the possibility that historians of science rarely if ever find that history progresses through the violent revolutions that Kuhn proposed (Reingold, 1980). Despite these issues with paradigms as an analytic frame, I contend that it is nonetheless useful in this chapter for me to utilize Kuhnian paradigms. As Koschmann explains,

Conducting a Kuhnian analysis […] is an instructive exercise, requiring a reexamination of the theories that have motivated work in the field and the practices by which technological innovations are designed and evaluated. Focusing on foundational theories and research practices, as opposed to the form and intended role of the designed artifacts, represents a novel way of conceptualizing the past (and future) work.

(1996, p. 3)

Adopting Kuhnian paradigms as a lens for constructing the history of digital technologies in PER serves to center my discussion on the educational theories and research efforts that underpinned much of the progress related to the topic. This is in contrast to the more typical reviews of digital technologies in PER (such as those that are listed in Table 2, Section 2.1.2), which tend to prioritize the features and design intentions behind specific digital tools.

In Section 2.4 of this chapter I will show that, perhaps ironically, taking a critical look at the application of paradigms is in itself a productive exercise.
for reflecting on the patterns and pitfalls of the digital technologies work of PER. After having laid out the historical progression and topical areas of the digital technologies work of PER, I will reflect on the how well the ‘paradigm’ label fits the larger changes in the landscape of this work. Among other things, I use Section 2.4 to address the question: how well does each new paradigm of the digital technologies work of PER resemble the fracturing of the PER community around issues of “terminology, conceptual frameworks, and views on what constitutes the legitimate questions of science” (Koschmann, 1996, p. 2)? Furthermore, with respect to the broader context of physics teaching, I address the related question: how much did the paradigm shifts in the digital technologies work of PER appear to sway the practices of physics educators?

2.1.2 Generation of topical areas

Beyond presenting the historical progression of the digital technologies work of PER, this chapter also presents an overview of the main topical areas of this literature base as I see them. Whereas the method for the historical portion of this chapter involves Kuhnian paradigms (discussed above), my generation of topical areas has involved me synthesizing and generalizing from the many similar characterization schemes of digital tools in science and physics education research literature since the late 1960s. In Table 2, I provide a list of these categorization schemes for the uses of the digital technologies, with references to examples of technologies identified by the respective authors.

Table 2. The taxonomies of digital technology use which I have consulted in building a list of the topical areas of digital technologies in PER (sources in bold specifically categorize educational technologies for the teaching and learning of physics).

<table>
<thead>
<tr>
<th>Source</th>
<th>Categorization scheme for the uses of digital technologies</th>
<th>Refs.†</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Zinn, 1967)</td>
<td>Drill</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Author-controlled tutorial mode</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Dialogue tutorial mode</td>
<td>3, 4</td>
</tr>
<tr>
<td></td>
<td>Simulation and gaming</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Retrieval and reorganization of information</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Problem solving with computation and display tools</td>
<td>7, 8</td>
</tr>
<tr>
<td></td>
<td>Artistic design and composition</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Handle records and recommend changes to the curriculum</td>
<td>9, 10</td>
</tr>
<tr>
<td></td>
<td>Assembling curriculum packages for students quickly</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Text editing</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Data analysis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Assistance with a first draft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Semiautomated generation of materials</td>
<td></td>
</tr>
<tr>
<td>(Zinn, 1968)</td>
<td>Drill and author-controlled tutorial</td>
<td>13, 14</td>
</tr>
<tr>
<td></td>
<td>‘Dialogue’ tutorial</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Simulation and gaming</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Scholarly aids: information handling, computation and display</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Computer aids for instructional management</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Computer-based tools for the author and researcher</td>
<td></td>
</tr>
<tr>
<td>Source</td>
<td>Category</td>
<td>Pages</td>
</tr>
<tr>
<td>--------</td>
<td>----------</td>
<td>-------</td>
</tr>
<tr>
<td>Schwarz, Kromhout, &amp; Edwards, 1969</td>
<td>Computational mode</td>
<td>15-18</td>
</tr>
<tr>
<td></td>
<td>Conversational mode</td>
<td>19-21</td>
</tr>
<tr>
<td></td>
<td>Simulation</td>
<td>22, 23</td>
</tr>
<tr>
<td></td>
<td>Films and other applications</td>
<td>24, 25</td>
</tr>
<tr>
<td>Blum &amp; Bork, 1973</td>
<td>Producer</td>
<td>24, 26, 27</td>
</tr>
<tr>
<td></td>
<td>Administrator</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Tutor</td>
<td>4, 28-36</td>
</tr>
<tr>
<td></td>
<td>Simulator</td>
<td>37-42</td>
</tr>
<tr>
<td></td>
<td>Calculator</td>
<td>43-48</td>
</tr>
<tr>
<td>Hinton, 1978</td>
<td>Computational aid</td>
<td>49, 50</td>
</tr>
<tr>
<td></td>
<td>Simulation</td>
<td>51, 52</td>
</tr>
<tr>
<td></td>
<td>Modeling</td>
<td>51, 53-57</td>
</tr>
<tr>
<td></td>
<td>Tutorial</td>
<td>52, 56</td>
</tr>
<tr>
<td></td>
<td>Computer aided instruction</td>
<td>52, 58</td>
</tr>
<tr>
<td></td>
<td>Programming</td>
<td>59-63</td>
</tr>
<tr>
<td></td>
<td>Problem solving</td>
<td>64-73</td>
</tr>
<tr>
<td>Bork, 1979</td>
<td>Interactive learning</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Individualization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Experience</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intellectual tool</td>
<td></td>
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<tr>
<td></td>
<td>Student control of pacing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Time and sequence control</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Student control over content</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Testing as a learning mode</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Management</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Communication</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Personal factors</td>
<td></td>
</tr>
<tr>
<td>Bork, 1981a</td>
<td>Intellectual tool</td>
<td>74, 18</td>
</tr>
<tr>
<td></td>
<td>Controllable worlds</td>
<td>75, 76</td>
</tr>
<tr>
<td></td>
<td>Testing and diagnostic aid</td>
<td>77</td>
</tr>
<tr>
<td>Solomon, 1986</td>
<td>Drill and Practice and Rote Learning</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>Socratic Interactions and Discovery Learning</td>
<td>79-81</td>
</tr>
<tr>
<td></td>
<td>Eclecticism and Heuristic Learning</td>
<td>82-85</td>
</tr>
<tr>
<td></td>
<td>Constructivism and Piagetian Learning</td>
<td>86-90</td>
</tr>
<tr>
<td>Wilson &amp; Redish, 1989</td>
<td>Drill and practice</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Testing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Course management</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tutorials</td>
<td>91, 92, 93</td>
</tr>
<tr>
<td></td>
<td>Dialogues and artificial intelligence</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Simulations</td>
<td>94-96</td>
</tr>
<tr>
<td></td>
<td>Instructional games</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Laboratory data acquisition</td>
<td>97, 98</td>
</tr>
<tr>
<td></td>
<td>Programming</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Modeling physics phenomena</td>
<td></td>
</tr>
<tr>
<td>Scanlon, O'Shea, Smith, Taylor, &amp; O'Malley, 1993</td>
<td>Hypothetical experiments</td>
<td></td>
</tr>
<tr>
<td></td>
<td>For breaking the laws of nature</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tidy experiments</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Instrumental data capture</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Direct mathematical modeling</td>
<td></td>
</tr>
</tbody>
</table>

2 Looking to put the sheer cost of computing in the early 70s into perspective, note that the ‘Tutor’ function described by Blum and Bork (1973) would cost anywhere from $12 to $140 per student per hour adjusted for inflation.
Ultimately, I examined each of these categorization schemes for the digital technologies related to PER and extracted what I saw to be the most compelling groupings. One commonly mentioned use of technology found in Table 2, especially in the early categorization schemes made before widespread use of personal computers, comprises the administering of grades, gathering of attendance, and/or organizing of materials for teaching. These implementations of technology, which would now likely fall into a category of learning...
management systems (LMSs), are among some of the most widely used technologies in all of education (M. Brown et al., 2015). The sheer prevalence of LMSs, and more importantly their lack of specificity for physics disciplinary learning, was reason enough for me to leave them out of the categorization generated in this thesis. Instead, I focused on creating categories such as Controllable Worlds that brought together many of the technological implementations listed separately in Table 2 (i.e., simulations, microworlds, and games), while spanning the breadth of technology-focused PER literature sources with which I have become familiar. The result is the following list of topical areas for the digital technologies work of PER: (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 (e-Learning). Each of these topical areas are discussed in Section 2.3.

2.1.3 Selection of articles

In generating the historical perspective and topical area map for this chapter, I have needed to scour through the existing literature on digital technologies in PER. The main approach I took in selecting the articles that appear throughout this chapter was the ‘backwards snowballing’ method (Jalali & Wohlin, 2012; Webster & Watson, 2002). This approach essentially entailed me finding several key contributions as starting points, typically by searching the term “computer” in PER literature databases such as Compadre (accessible at compadre.org/per), and following the chain of relevant literature cited within those starting points backward to new articles. Each relevant article identified from the starting article then became a potential source for additional backward citation searches (hence the label ‘snowballing’). An illustrative example of this process can be seen with the Wilson and Redish (1989) paper on Using Computers in Teaching Physics. This article came up early on in my database searches and, having identified Redish as a well-cited author in PER, I deemed it a worthwhile candidate for a starting point in my literature search. This particular Wilson and Redish (1989) paper lead me to Bork (1978), a key physicist-turned-education-researcher from the years preceding ‘proper’ PER. A consideration of Bork’s publications opened up much of what became the first paradigm in my review of the digital technologies work of PER.

While the backwards snowballing method of literature review is by no means infallible, one relevant finding from Jalali and Wohlin (2012) is that such an approach is unlikely to lead to different findings in a broad sense compared to an approach based on exhaustive database searching alone. Thus, especially with respect to the larger themes I identify in the PER literature with respect to digital technologies, there is some precedential reason to believe that other related methods would have revealed the same results. That being said, it is reasonable to expect that altogether different approaches to
literature review such as natural language processing (e.g., Odden, Marin, et al., 2020) may reveal something that has remained altogether undetected in my approach. In the sections that follow, I will present the digital technologies work of PER starting with the historical progression of this work over the course of the last 60 or so years.

2.2 The paradigms of the digital technologies work of PER

As mentioned in Section 2.1.1, Koschmann (1996) describes four key paradigms in instructional technology research: namely (1) Computer-Assisted Instruction, (2) Intelligent Tutoring Systems, (3) Logo-as-Latin, and (4) Computer-Supported Collaborative Learning. In adapting Koschmann’s description of instructional technology research in general for my focus on physics education, I have devised three paradigms of digital technologies work in PER, keeping the first and last of the paradigms identified by Koschmann: namely, I portray the history of this field of research through the paradigms of (1) Computer-Assisted Instruction, (2) Computer Constructivism, and (3) Computer-Supported Collaborative Learning. In presenting and discussing each of these three paradigms, I will first present the broader context of PER work that was conducted within the same time frame. Then, I will detail the work that was conducted within that period of PER involving digital technologies, specifically highlighting the technological progress and shifting tides in education research that coincided with the emergence of each paradigm.

As I will discuss below, my departure from Koschmann’s paradigms—in leaving out the Intelligent Tutoring Systems and Logo-as-Latin paradigms and incorporating the Computer Constructivism paradigm—was inspired by the fact that some of the paradigmatically-salient occurrences that affected instructional technology in general had less of an apparent impact within the PER community. Likewise, in conceptualizing the second paradigm of the digital technologies work of PER, unique developments of technology tailored for physics as a discipline (i.e., technological advancements that catered directly to the physics’ emphasis as a discipline on computational problem solving and laboratory work) led me to conceive of a paradigm—Computer Constructivism—which was largely absent from the broader field of instructional technology as reported by Koschmann. It is also worth mentioning that the efforts around the digital technologies in PER that I discuss in the following sections were as much the result of the chronological progression of technological advances as they were the engine reflexively driving the development of future technology. While there were 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 the work of those physics education researchers interested in digital technologies.

2.2.1 Computer-Assisted Instruction: leading up to the 1970s

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)

The first paradigm I identify in the digital technologies work of PER, stretching up until sometime in the early 1970s, is the Computer-Assisted Instruction (CAI) paradigm. This paradigm emerged on the heels of WWII and the launch of Sputnik, two historical watersheds that demonstrated the capacity of technology for addressing the big issues of the world and, accordingly, primed the appetites of many governments for a combative scramble around innovation in education. As I will discuss below, those working on transforming education with computers in this paradigm largely aimed to provide students with a responsive, individualized instructional tool for the efficient transmission of information.

The broader PER context: the ‘Prelude’ years

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 curriculum projects aimed at developing science teaching materials. On the topic of learning theories, American education theorist/philosopher John Dewey (1938) and Swiss 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) (O. 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 (O. 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 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 Co-operation (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 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) as a working group to improve physics education (Koupil, 2008). Similarly, in 1960, the International Union on Pure and Applied Physics (IUPAP) held the first International Conference on Physics Education, which later that year led to the development of the International Commission on Physics Education (ICPE) (French, 1980).

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 (Cummings, 2011). Frederick Rief, a physicist with previous 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 de-

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3 Written in the original French: Groupe International de Recherche sur l’Enseignement de la Physique.
velopment projects, the 1970s had sufficient means for the emergence of modern PER. Cummings (2011) refers to this period leading up to 1970 in the U.S. as the “Prelude” years for PER (p. 10).

**Computer-Assisted Instruction in PER’s ‘Prelude’ years**

During PER’s Prelude years, the inclusion of digital technologies (namely, the computer) in physics education reform efforts was perhaps an obvious choice for curriculum developers, especially since the watershed launch of Sputnik in 1957 had ostensibly functioned as a technological challenge from the Soviet Union (Cummings, 2011; Meltzer & Otero, 2015). As William C. Kelly, co-founder of ICPE, put it, “[the Soviet Union] sending a satellite into earth orbit was a more technological achievement than a scientific one, of course, but in the mind of the public the two were indistinguishable” (Kelly, 1985, p. 1). Soon after the Soviet satellite was sent into orbit, several universities began developing computer-based curricular materials for science and engineering education (Schwarz et al., 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). 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 for students to solve (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, a 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, 1965a) and the Conference on the Uses of the Computer in Undergraduate Physics Instruction (Commission on College Physics, 1965b). In 1966, the Educational Technology journal was founded (JSTOR, 2019). By 1969, as many as 27 major 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 work done with digital technologies during this time includes

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4 Altogether, 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).

Efforts to involve computers in physics education that 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 that I will refer to as Computer-Assisted Instruction (CAI). In his discussion of the paradigmatic shifts of ‘instructional technology research,’ Koschmann (1996) splits the 1960s and 1970s into two separate paradigms, namely a Computer-Assisted Instruction (CAI) paradigm and an Intelligent Tutoring Systems paradigm, respectively. However, as it seems to me that the physics community did not see the level of immigration from the field of artificial intelligence research as did instructional technology research in general, the digital technologies work of PER did not undergo the same ground shift toward an Intelligent Tutoring Systems paradigm as Koschmann defines it. 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.

As will become an apparent pattern in my discussion of the other paradigms in digital technologies work of PER, the CAI paradigm was in many ways a product of the available computing technology at the time. Researchers in this era were spurred on by the advent of the transistor, the integrated circuit, and (subsequently) time-shared computing. 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. As such, the computers that were available to CAI researchers signified a stark departure from the sluggish, vacuum tube computers of before. An early pioneer in instructional technology 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 each have their own 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. 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). 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 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 constant feedback on their understanding (à la operant conditioning) via an interaction 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 often suggested by many researchers at the time that the computer could take on a variety of roles in the science classroom (see the first rows of Table 2, Section 2.1.2). It was during the CAI-paradigm era that the many of the later-dominant modes of computer use were first implemented. Alfred M. Bork, perhaps the most prolific physics education reformer concerned with digital technologies in the CAI-paradigm era, wrote the following 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)

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5 Yes, 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 instructional technology, 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).
For Bork and Blum, computer usage in the ‘producer’ mode involved the creation of films (i.e., frame-by-frame graphs), illustrations, and textbooks. 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 (e.g., a position vs. time graph of a damped harmonic oscillator based on specified initial conditions; 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 notion of 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, ‘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 the digital technologies work of PER.

2.2.2 Computer Constructivism: 1970s-1990s

Solving a mathematical problem is a process of construction. The activity of programming a computer is uniquely well suited to transmitting this idea.

(Feurzeig et al., 1969, p. 14)

I refer to the second paradigm in the digital technologies work of PER, spanning from the 1970s to the 1990s, as the Computer Constructivism (CC) paradigm. This paradigm came at a time when the microprocessor provided an order of magnitude increase in computing power per student, which in turn made it possible for each physics student to use digital technologies in increasingly creative ways. Simultaneously, as the field of PER began to take shape, physics education researchers within this paradigm tended to see the computer as a tool with which students could actively construct meaning.

The broader PER context: the ‘Early Years’

In the two decades following the ‘Prelude’ years of PER—the next period which Cummings (2011) labels as the “Early Years” (p. 12)—modern PER at university level truly began. From the 1970s through the 1980s, interested academics began to develop investigative research techniques, started amassing

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6 Side note: it should be noted that, while the first Computer-Assisted Instruction paradigm (Section 2.2.1) and the last Computer-Supported Collaborative Learning paradigm (Section 2.2.3) utilize labels that are actually used by researchers to describe the type of work they do, the ‘Computer Constructivism’ label is one which I have invented for the purposes of this thesis.
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 et al., 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 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 innovation of microprocessors, other physics education researchers 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).

A key aspect of the ‘Early Years’ of PER was 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’” (O. De Jong, 2007, p. 17) in order to better understand the learning process itself. As part of this effort, early physics education researchers documented physics students’ pre-classroom ideas that were shaped through everyday experiences and brought into the context of physics learning. 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., Helm, 1978; 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 (e.g., see Reference 3 in Trowbridge & McDermott, 1981). By 1989, the collection of few physicists who had started to pursue PER at the university level in the 1970s had increased to the point that as many as ten American universities housed PER faculty members in their departments of physics.

**Computer Constructivism in PER’s ‘Early Years’**

Following the advent of the microprocessor in 1971, the prospect of time-

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7 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.
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, physics educators saw a marked increase in the potential computing power at the disposal of each student. Time-shared computing had required that low-demand packages be used by each individual type-writer 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 including 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 class wide implementation with 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. In the constructionist perspective on learning, students were tasked with designing, building, and debugging computer programs in order to become more fluent in the systematicity inherent in computers’ infrastructure. 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-adopted perspective of constructivism. A good example of constructionism-influenced teaching approaches is that of problem-based learning (PBL) (e.g., Sahin, 2010). Students in PBL settings are encouraged to actively produce (construct) objects in the physical/digital world in the process of learning through discovery.

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 and the constructionist perspective on learning has played a significant role in the work of this thesis. Especially in the period from the 1970s to the 1990s, the Logo programming language and constructionism were massively influential in instructional technology, so much so that in his paradigmatic review of instructional technology literature, Koschmann (1996) describes the instructional technology paradigm that emerged in the 1980s as “Logo-as-Latin.” Koschmann chooses this name because students’ use of programming languages like Logo was intended to serve them generally across diverse educational objectives (Koschmann, 1996, 1997). That is, in a sense, these programming languages were argued to have the “diffuse cognitive benefits [that were] reminiscent of arguments advanced for the study of classical languages” (Koschmann, 1997, p. 409). However, within PER there were other implementations of digital technologies influenced by constructivist/constructionist theories of learning—especially computational programming and microcomputer-based laboratory tools as I explain below. As such, I see it worthwhile to depart from Koschmann’s label and have opted to refer to this paradigm as Computer Constructivism in the digital technologies work of PER.

Around the same time as Papert’s work with Logo, while PER was now well in the ‘Early Years’ of its development (Cummings, 2011), early physics education researchers took advantage of the capabilities of personal computers in other ways more specific to the topic of physics. In 1983, Edward Redish and Jack M. Wilson started the Maryland University Project in Physics and Educational Technology (MUPPET) as a means for exposing introductory physics students to computational programming at the start of their traditional calculus-based course (Redish & Wilson, 1993). Projects like MUPPET made use of the newly-accomplished leaps in computational power to introduce mathematically-complex concepts earlier in a student’s career than their mathematical proficiency would normally permit. 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

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8 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).
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 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.

(1993, p. 223)

To a degree, the computational programming efforts of this era were the fulfillment of the programming-rich introductory physics courses which Alfred Bork had envisioned in the 1960s (e.g., Bork, 1964, 1968), finally 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 revolution also allowed for the creation of computer-based tools that 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 (discussed more with the next paradigm), these efforts produced innovative technology-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 analyzed, 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 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 paradigm of Computer Constructivism (CC). Researchers were making use of the insights of the constructivist perspective on learning, which by this time had all but replaced the transmissionist perspectives of many physics educators and physics education researchers in the decades prior, alongside a microprocessor-fueled revolution in computing power. Especially in relation to the previous CAI paradigm, it is important to note how CC efforts in the digital technologies work of PER were no longer emphasizing the need for the computer to be a delivery system of carefully curated content. Instead, the technology-focused 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 with microprocessor-enabled sensors.

2.2.3 Computer-Supported Collaborative Learning: 1990s-now

All relations should be seen as both social and technical […]. Purely social relations are found only in the imaginations of sociologists, among baboons, or possibly, on nudist beaches; and purely technical relations are found only in the wilder reaches of science fiction. […] Indeed, what we call the social is bound together as much by the technical as by the social.

(Law & Bijker, 1997, p. 290)

I refer to the third and final paradigm of the digital technologies work of PER as the Computer-Supported Collaborative Learning (CSCL) paradigm—in line with the final paradigm originally identified by Koschmann (1996). This paradigm emerged in the 1990s as the newly-public Internet began to demonstrate the potential for technology to act as a socially-connective medium unlike anything the world had seen. Within this context, as PER produced some of the most influential curricular artefacts to date, some physics education researchers also began to incorporate theories that attended to the socio-cultural aspects of learning physics.

The broader PER context: the ‘Formative Years’ and onward

From 1990 to around 1998, in an era termed the “Formative Years” of PER by Cummings (2011, p. 15), many influential events occurred for the field. For one, Edward Redish—the physics education researcher from the University of Maryland who with the MUPPET project had studied how to incorporate computer programming in the physics classroom since the mid-1980s—went on 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, see p. 15). Whether spurred on by Redish or otherwise motivated, 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), 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. Still, the consistently poor results of university physics students often showed how scarce a conceptual understanding of physics was, even at highly-ranked institutions. In 1998, Hake published an 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. Though the FCI is widely considered to be one of the first and most influential of the concept tests in PER, work had already been done outside the U.S. more than a decade prior in South Africa to test students’ difficulties with physical concepts (Helm, 1978).

It was also during this period that the majority of PER’s ‘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 published his widely popular Peer Instruction approach during this time (Mazur, 1997). Other curricula published in these “Formative Years” of PER include Modeling Instruction (Hestenes, 1992; Jackson et al., 2005; Wells et al., 1995), Workshop Physics (Laws, 1991; Laws et al., 2015), Physics by Inquiry (McDermott, Shaffer, & Rosenquist, 1996), and Tutorials in Introductory Physics (McDermott et al., 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 been the international trend in science education research (O. De Jong, 2007)—PER since the late 1990s has begun embracing a diversity of learning theories (e.g., Brewe et al., 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 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 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*, as many as 50-80 PER publications were routinely produced per year as of 2014. At the time of writing this thesis, roughly 90 PER articles per year are now published per year in *Physical Review*, some 230 PER articles per year are published in *Physics Education*, and around 80 PER articles per year are published in the *European Journal of Physics*. 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.

**Computer-Supported Collaborative Learning in PER’s Formative Years**

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 software that tended to isolate individuals from one another, a new movement emerged within the digital technologies work of PER to investigate the collaboration of students during technology-supported learning (Stahl et al., 2006). Much of this movement, located largely outside of the PER work in the U.S., 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 et al. 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 et al. (1989)—both within PER and also more broadly in science education research across the western world (O. 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 through which students interact (e.g., email, chat, discussion forums, videoconferencing, etc.) and (2) where the computer meaningfully scaffolds interactions between students in person. Within the former camp, PER work has in the past mostly been characterized by investigating the effectiveness of MOOCs (Massive Open Online Courses) (e.g., Dubson et al., 2014). The current COVID-19 pandemic at time of writing (Schleicher, 2020; United Nations, 2020) has recently forced an overwhelming proportion of teaching and learning into distance learning through videoconferencing classrooms. As such, there is a wave of new research into the effectiveness of computer-mediated learning (e.g., Chang & Fang, 2020; Guo, 2020; Pols, 2020), which will likely fit within this former camp of CSCL work. Within the latter camp—i.e., where the computer supports in person interaction—PER work has tended to focus on how small student groups work with digital technology like interactive whiteboards (e.g., Gregorcic, 2015b; Gregorcic, Etkina, & Planinsic, 2017; Gregorcic & Haglund, 2018), infrared cameras (Samuelsson et al., 2019), and MBL tools like the iOLab (Volkwyn et al., 2018; Volkwyn et al., 2020; Volkwyn et al., 2020).

However, while there has certainly been a growing number of physics education researchers investigating digital technologies use with socially-cognizant theoretical 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. Despite the term not being common parlance for most physics education researchers (American researchers in particular), the PER work I see as aligning with the CSCL paradigm marks a departure from the CC paradigm. Perhaps, as Koschmann suggests in his paradigmatic review of instructional technology, it remains a question whether or not CSCL constitutes a new paradigm for research in these communities (Koschmann, 1996). Or perhaps still, since this era has seen a significant amount of other digital technologies work in PER 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 et al., 2014; B. Sherwood, 1971; S. Smith & Sherwood, 1976) and web-based homework programs like *Mastering Physics* are examples of recent CAI-paradigm work (Bonham et al., 2003; Cheng et al., 2004; Kashy et al., 1995, 1993; Kortemeyer et al., 2008; Lee et al., 2008; Pascarella, 2002). *Physlets* (Christian & Belloni, 2001; Dancy et al., 2002) and the widely-used PhET simulations (W. Adams et al., 2015; W. Adams, Paulson, et al., 2008; W. Adams, Reid, et al., 2008a; K. Perkins et al., 2006; Wieman et al., 2010; Wieman et al., 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 sufficiently noteworthy subset of digital technologies work in PER that aims to highlight the ways in which digital technology can facilitate and augment the collaborative learning of physics content. A summary of the characteristics of the CSCL paradigm, as well as the characteristics of the CAI and CC paradigms, can be found in Table 3.

Table 3. A summary of the paradigms identified in the historical progression of the digital technologies work of PER.

<table>
<thead>
<tr>
<th>Paradigm</th>
<th>Theory of Learning (learning is…)</th>
<th>Role of Technology (technology should…)</th>
<th>Technological innovations (technology is…)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAI (up to the 70s)</td>
<td>acquisition of knowledge with quick, corrective feedback (Behaviorism)</td>
<td>act as <em>teacher/tutor</em>, sharing content efficiently and determining if students have learned what is shared</td>
<td>transistors, integrated circuits, mainframe computers, timeshared computing, typewriter terminals</td>
</tr>
<tr>
<td>CC (70s to 90s)</td>
<td>active construction of new knowledge (Constructivism)</td>
<td>act as a <em>systematic environment</em>, allowing students to build worlds and calculate; also, act as a <em>sensor</em> for probing the physical world</td>
<td>microprocessors, personal computers, microcomputer sensors</td>
</tr>
<tr>
<td>CSCL (90s onward)</td>
<td>activity in social contexts (Social Constructivism &amp; Situated Cognition)</td>
<td>act as <em>facilitator</em> of the interpersonal act of learning among students and teachers</td>
<td>Internet, smartphones, large-touchscreens, haptic feedback, virtual reality</td>
</tr>
</tbody>
</table>

2.3 The topical areas of the digital technologies work of PER

Having now reviewed the historical progression of work on digital technologies in PER, I turn my attention to a summary of the topical areas of this work. As I explain in Section 2.1.2, I have examined the various taxonomies for digital technology use and development in science education and ultimately
devised the following seven topical areas: (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 (e-Learning). In this section I summarize some of the relevant research within each of these topical areas to illustrate the diversity of current work involving digital technologies in PER.

**Controllable Worlds: Simulations, Microworlds, and Games**

As I discussed in the history part of my literature review, 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 digital learning environments (DLEs) bear a striking resemblance to the computational simulations used by physicists to treat analytically-elusive phenomena, they are often referred to as *simulations.* Some of 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, 1965b; Leonard & Wing, 1967; Luehrmann, 1967; Rosenburg, 1965; Schwarz et al., 1969).

Arguably the most widely-used, PER-based collection of physics learning simulations are the PhET 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’—an aesthetic that includes such features as intuitive controls, ‘correct’ visual representations of physics models, everyday objects and situations, etc.—developed through extensive feedback from student interviews (W. Adams et al., 2006; W. Adams, Reid, et al., 2008b, 2008a). Recently, the PhET team has put an emphasis on developing their simulations to be accessible (Morgan & Moore, 2016; K. 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), *GeoGebra* (Arnone et al., 2017; Hohenwarter & Fuchs, 2004; Lingefjärd & Ghosh, 2016; Solvang & Haglund, 2019), and the more recent *QuVis* simulations (Kohnle et al., 2012).

Simulations have long 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 &

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9 Otherwise referred to by such names as interactive computer-based simulations (ICBS, Zacharia, 2003), interactive simulations (White, 1992), participatory simulations (Wilensky & Stroup, 1999), computer-based manipulatives (Horwitz & Christie, 2000), etc.
Anderson, 2003). As I alluded to in my historical review of the digital technologies work of PER, much of the early PER work was inspired by the realization that students had difficulties in understanding fundamental physics concepts. Researchers have since amassed an abundance of documented examples of common student difficulties in physics—around 115 studies on students’ ‘misconceptions’ 10 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 et al., 2000; Etkina et al., 2005) and that instructional tools which can reliably aid students in overcoming difficulties are generally slow to develop (D. Brown & Clement, 1989; Camp & Clement, 1994; Clement, 1993; Sokoloff & Thornton, 1997; Strike & Posner, 1982). Physics simulations are by and large examples of DLEs designed for ‘conceptual change.’ 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 et al., 1994), optics (Eylon et al., 1996; F. Goldberg, 1997), waves (Grayson & Donnelly, 1996), modern physics (Steinberg et al., 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 for 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, et al., 2005).

However, while it may be common to label this entire category of DLEs 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 simulation-like DLEs (see Chapter 3 and Chapter 8 for more on this). For now, it is important to acknowledge a distinction in the PER literature between simulations, microworlds, and games. These simulated environments constitute a single topical area of the digital technologies work of PER that I refer to as Controllable Worlds. Here, I borrow the term ‘controllable worlds’ from Bork (1981a), who used the phrase to refer to computer use in physics courses that could “[build] up a student’s insight or intuition” (p. 26). To reiterate what I mean with the term, I use Controllable Worlds to refer to the subset of digital (educational) technologies—including simulations, microworlds and games—that provide users with control over manipulable virtual environments.

10 The term “misconceptions” (and to a lesser degree, the terms “alternative conceptions,” “pre-conceptions,” 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.
Simulations (like those described above) are DLEs that allow students to interact with pre-built models of real or hypothesized situations (National Research Council, 2011). These DLEs are typically designed around a specific phenomenon or set of phenomena so as to provide students with access to particular disciplinary concepts. The term microworld comes from Papert’s (1980) work with Logo and constructionism (as introduced in Section 2.2.2; see also, Sections 3.2 and 5.2.1). Microworlds are often thought of as DLEs that offer more opportunities for creativity and invention than what is typically offered by simulations (Plass & Schwartz, 2014). While simulations tend to allow users to explore the effects of a set of parameters within the given phenomenon, microworlds are imagined to 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). The nature of the distinction between the DLEs often labelled ‘simulations’ and ‘microworlds’ is of particular relevance to this thesis. I argue in Chapter 3 and Chapter 8 for descriptions of these DLEs (and others) that necessarily considers their function when embedded in the context of broader learning environments.

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 et al., 2003; Miller et al., 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 such DLEs to become educationally useful (Rieber, 2005; White, 1984; though I do not align with this viewpoint entirely, see also my discussion of imposed structure through responsive teaching in Chapter 7). 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 et al., 1989; Pea & Kurland, 1984).

The third kind of Controllable World which exists in the digital technologies work of PER—and to which my work does not as readily relate—is that
of digital games. When comparing digital games to simulations and microworlds, Rieber (2005) 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 (Clark et al., 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 the digital technologies work of PER 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 designed to support a wide variety of interactional modalities such as gestures (Pavlovic et al., 1997), speech (Potamianos et al., 2013), haptics (Benali-Khoudja et al., 2004), eye blinks (Grauman et al., 2003), and more (Jaimes & Sebe, 2007). Researchers within science education have examined how haptic feedback affects students’ use of multiple representations (e.g., Schönborn et al., 2011) and how augmented reality setups can encourage conceptual understanding about nanotechnology (e.g., Schönborn, Höst, Palmerius, & Flint, 2014). In this thesis, I draw on the work done around interactive whiteboard (IWB) use during physics learning. On this topic, physics education researchers have explored how IWBs support students’ physical engagement during physics learning (Gregorcic, 2015a, 2015b; Gregorcic et al., 2015; Gregorcic, Etkina, et al., 2017; Gregorcic, Planinsic, et al., 2017; Mellingsæter & Bungum, 2015). It has been theorized, for example, that large touch screens can allow students to intuitively 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 on the role that a large touchscreen can play in students’ physics-relevant interactions in Section 3.5.

One ‘emerging’ technology within the topical area of Human and Computer Interfaces is that of virtual reality (VR), mixed reality (MR), and augmented reality (AR) interfaces. Typically, VR interfaces are implemented as a means of granting users immersion into stereoscopic, 3D Controllable Worlds (e.g., Brna, 1999; Kaufmann & Meyer, 2009; Porter et al., 2020; J. Smith et al., 2018).

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11 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 5.1).

12 Porter et al. (2020) explain that VR efforts in physics date as far back as the mid-1990s.
Probeware (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 microcomputer-based laboratory tools—otherwise called simply MBLs or probeware—has shown improvements in students’ conceptual understanding of kinematics and graphs (Brasell, 1987; Thornton & Sokoloff, 1990) as well as dynamics (Thornton & Sokoloff, Sokoloff, 1997). Thornton and Sokoloff (1990) explain how and why they see probeware 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 probeware 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 probeware 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 probeware such as the iOLab or infrared cameras can be studied in small group work with social semiotics (Samuelsson et al., 2019; Volkwyn et al., 2019, 2018; Volkwyn, Airey, et al., 2020; Volkwyn, Gregorcic, et al., 2020). For further reading on this topical area, Tinker (2000) provides a personalized history of probeware and Trumper (2003) offers a further review of probeware/MBLs in the context of the physics laboratory.

Programming

Starting in the era of pre-PER curricula development projects, Alfred M. Bork was an early proponent of programming in the physics classroom. Among other efforts, he devised an introductory college physics course around The Feynman Lectures on Physics (Feynman et al., 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 where later used as part of the Comprehensive Unified Physics Learning Environment (CUPLE) project (Redish et al., 1992) and the CUPLE physics studio (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

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13 Tinker (2000) explains that, due to the ‘microcomputer’ part of the MBL acronym dating the term, the newer term ‘probeware’ (attributed to Marcia Linn) is much more apt for these digital technologies.
structure of the programming language.\textsuperscript{14} Other more recent work on programming environments includes the application of social semiotics (Svensson et al., 2020) and so-called ‘computational essays’ (Odden & Caballero, 2020). 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). In this thesis, I do not focus directly on programming environments, except to include them in my broader discussion of DLEs in Chapters 3 and 8.

\textbf{Students Response Systems (Clickers)}

Student response systems (SRSs), can be considered a family of handheld digital devices that can be used by students to wirelessly respond to teacher prompts, especially in lecture-based settings. Also known as ‘clickers,’ these tools were first developed by the US military in the 1950s (Abrahamson, 2006) and eventually came into use at both Stanford University and Cornell University by the late 1960s (Aljaloud et al., 2015). The iClicker system, currently self-reported as the ‘market leader’ in SRS technology, 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). SRS use is particularly common in science classrooms, 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\textsuperscript{15} (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 lectures. PER scholars have found that SRSs are viewed by physics students to be predominantly useful, especially when the technology is implemented alongside 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 et al. 2016). For a more in-depth (albeit not physics-specific) discussion of SRS technology, see Aljaloud et al. (2015).

\textbf{Tutors and Video}

Much of the early digital technologies work of PER 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., 1995, 1993;

\textsuperscript{14} In this latter sense, programming in physics instruction aligns well with Papert’s vision for students using microworlds to become familiar with the latent systematicity of computers—i.e., with the Logo programming language (see Section 5.1).

\textsuperscript{15} 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).
Kortemeyer et al., 2008; Lee et al., 2008; Pascarella, 2002) and/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 et al., 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 et al., 2014; Zollman & Fuller, 1994), since videos have been a relatively common addition to CAI methods. Nonetheless, a case could certainly be made that the PER work on interactive video deserves a topical area of its own, as in many ways this work helped usher multimedia digital 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 touting to democratize access to learning, minimize costs, and reach larger audiences than in-person instructional methods. Within PER, investigations around distance learning have historically 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 et al., 2015). Other physics education researchers have examined students peer discussion online (Duda et al., 2008; Kelley et al., 2018) or examined the results of concept tests in distance learning environments (Aiken et al., 2014; Chudzicki et al., 2015). The COVID-19 situation at the time of writing (Schleicher, 2020; United Nations, 2020), with the associated ‘social distancing’ recommendations from the Center for Disease Control and the World Health Organization, has forced much of the typically in-person physics instruction to switch to distance learning. As such, there is a surge of new research efforts within this topical area aimed at determining the impact of this migration from brick and mortar classrooms to videoconferencing-based teaching and learning (e.g., Fields et al., 2020; Gavrin, 2020; Hamdan & Buxner, 2020).

### 2.4 Discussion of the digital technologies work of PER

Having presented the paradigmatic (historical) development and the diversity of topical areas related to the digital technologies work of PER, I will now discuss some of the patterns that appear across this subset of literature. In the context of this thesis, such a discussion will reveal how my doctoral research
work stands to contribute to PER and other scholarly communities dealing with digital technologies research. More broadly, this section will provide some speculative insights into what the future holds for technology in physics education. To begin, as promised in Section 2.1.1, I will first assess the degree to which the historical paradigms I identified in the literature on the digital technologies work of PER are justifiably seen as paradigms.

CAI, CC, and CSCL: are these really paradigms?
In addressing whether or not the three paradigms I identified in Section 2.2 are justifiably labelled as paradigms, I ultimately seek to evaluate how well the periods I labelled as CAI, CC, and CSCL ‘paradigms’ entail the fracturing of the PER community around issues of “terminology, conceptual frameworks, and views on what constitutes the legitimate questions of science” (Koschmann, 1996, p. 2). While a full discussion of this point may merit many more words than I will devote to it here in this thesis, the stance I take on this matter is that the CAI, CC, and CAI work in PER were not distinct paradigms in the way that Kuhn intended the term be used. Instead, I see CAI, CC, and CSCL as three meaningful ‘periods’ within the digital technologies work of PER, each echoing the consequential ground shifts associated with other paradigmatic revolutions in PER and in technology more broadly.

As noted in Section 2.2, there were certainly differences in ‘conceptual frameworks’ associated with the paradigms I identified. The founding of PER as a legitimate field of research in the 1970s marked a paradigm shift in the dominant learning theories (transmissionist to constructivist) and again to a lesser degree in the late 1990s, a conceptual framework paradigm shift occurred within PER (constructivist to social constructivist). Likewise, the role of technology in education and society at large changed as consecutive innovations caused a shift in the broader conception of what technology could and should do. However, each of these revolutionary shifts were largely fought and won within those broader contexts rather than within the digital technologies work of PER itself. This is to say, while the examination and characterization of the digital technologies work of PER into the three ‘paradigms’ above is an effective exercise for revealing the contextual shifts that occurred surrounding that digital technologies work, ultimately the digital technologies work itself was not the locale for the revolutionary shifts that would justify them being seen as proper paradigms.

2.4.1 A pattern in the digital technologies work of PER
It is fitting now to reflect on some patterns and pitfalls that can be found across the digital technologies work of PER and that have persisted throughout the past and present sensibilities around role of digital technology within physics education. The most salient pattern I see in the digital technologies work of PER is a bias in the literature toward the design of new tools rather than the
exploration and recommendation for how teachers and students might make
the best use of the tools the PER community already has. A mindset that per-
vaded the mid-century CAI work I collected, for instance, appeared to be that
physics education would be better served through innovation and technologi-
cal troubleshooting than through the development of sound teaching practices
involving the tools of the time. This was perhaps understandable at that time
due to the culturally-salient impact of the space race triumphs via technologi-
cal innovation.

Though it has necessarily taken on different justifications, this innovation-
seeking mentality in the digital technologies work of PER seems to have
largely persisted in the many decades since. The personal computer boom of
the CC era carried with it a revolutionist’s spirit of wrenching the power of
computers away from the “large, centralized, bureaucratic institutions” such
that it might become a “symbol of individual expression and liberation”
(Markoff, 2005, p. xii; see also Turner, 2006)—again pitting technology as a
silver bullet of sorts, this time against the centralized powers of governmental
military-industrial complexes. With the Internet in the CSCL era, technologi-
cal innovation was proselytized as a grand connector of humans around the
globe. Thus, echoing the techno-enthusiasm of the CAI period, the CC and
CSCL work I gathered during my literature search seemed to carry with it the
notion that this time, as opposed to those naïve technological attempts of yes-
teryear, the innovations within the digital technologies sphere would remedy
the challenges facing physics education by virtue of new technological capa-
bility.

It is worth noting that, in my focus on the ‘paradigms’ of the digital tech-
nologies work of PER, I have intendionally sought out the ‘revolutions’ that
have occurred across that thread of history. This may have had the effect of
disproportionately selecting for this pattern of innovation during my literature
search. My predisposition notwithstanding, however, I suggest that the under-
pinnings and implications of a design-focused approach to digital technologies
within PER are worth discussing.

First, I will speculate on where an emphasis on technology design as a so-
lution to education problems might come from: namely, it may be that design
is generally what career physicists do to solve problems. Designing apparat-
uses and engineering specialized equipment is something of a trade standard
for physicists more broadly. It should perhaps be unsurprising, then, that when
the experimentalists of physics labs have turned their attention to matters of
the physics classroom (a common path for new researchers getting into PER;
Cummings, 2011), these trained apparatus designers/engineers have had the
compulsion to wield the latest breakthroughs in technology to design/engineer
a ‘fix’ to the physics classroom. In this way, digital learning technologies
might appear as a somewhat natural application of the skill set honed by ex-
perimentalist physicists. As Kuhn—a ‘career scientist’ himself—points out in
The Structure of Scientific Revolutions, the main “raison d’être [of technology] is an external social need” (1970, p. 19). It follows from this perspective that a social need such as the ‘improvement of physics education’ implies the existence of a bespoke technological solution.

Nonetheless, PER’s pattern of emphasizing design in technology work carries with it two important implications for physics teaching and learning, which are arguably more critical to consider than the question of why such a mentality is so prevalent in the PER literature. First, the design-focused approach implicitly deemphasizes the individuality and competence of physics teachers. Ferster (2014) describes this as a ‘teacher proofing’ compulsion in education technology design. Teacher proofing is “the practice of limiting the autonomy of individual teachers to produce a more uniform and controlled experience” (Ferster, 2014, p. 1) for learners, specifically through technology. The most generous arguments for teacher proofing are that it is a practice that benefits teachers who do not have time to develop a specialized skillset with a new technology and that it standardizes students’ experiences of the material in turn-key fashion. However, until digital learning technologies have made massive strides beyond current capabilities, genuine teacher proofing is on the whole unrealistic: educational technologies are only as good as the way they are pedagogically implemented (see the related discussion around technical vs. pedagogical interactivity; e.g., Murcia, 2014; Smith et al. 2005). The outside-in approach of designing and applying teacher-proof digital technologies to physics learning environments might even alienate the very teachers needed to implement the technologies effectively:

Cohorts of reformers for the past century have dreamed of instructional [technologies] overhauling traditional teaching practices and wrestled with the conundrum of asking the very people thought to be causing the problem to carry out the change.

(Cuban, 2018, p. 181)

Thus, by devaluing the target audience of users (i.e., the teachers needing to carry out the change), the PER work related to digital technologies that prioritizes the design of newer and better teacher-proofed technologies runs the risk of working across purposes for improving physics education.

Another implication of PER’s overemphasis on design in technology work is that it increases the likelihood of there being a misalignment between what is made for physics education and what is needed to be made for physics education (Dawes, 1999; Granger, Morbey, Lotherington, Owston, & Wideman, 2002; Sara Hennessy, 2006; Wellington, 2005). It is safe to say that the general capabilities of digital technology will continue to be innovated and revolutionized. However, this does not necessitate that the majority of PER attention to technology be focused on shoeorning the latest (or for that matter, easiest-to-shoeorn) technology into the physics learning environments as a response.
The somewhat apocryphal over-prescription of interactive whiteboards to whole countries of classrooms that never asked for them, for example, is a testament to this misalignment (see Hennessy, 2011; Warwick & Kershner, 2008). Countless teachers found their classrooms outfitted with large touchscreens in the place of the more familiar dry-erase whiteboards despite no demonstrable need for the change. Proponents of such technological ‘injections’ may hope for positive transformations in teaching practices as a result of the presence of innovative technologies. However, there is considerable evidence that teachers who utilize such new technologies often do so in a manner that preserves the teaching practices they engaged in before the technology arrived (Cuban, 2001, 2018).

The irony of all this, then, is that PER’s emphasis on technology design has been by some accounts largely ineffectual for the wholesale transformation of physics education:

In almost every other area of our modern world, machines have significantly contributed to modern life, but they are largely missing from our schools. A nineteenth-century visitor would feel quite at home in a modern classroom, even at our most elite institutions of higher learning.

(Ferster, 2014, p. 1)

This is not to say that digital technologies are absent from physics education per se, but more so an admission that the technologies that tend to be picked up and stick around in the physics classroom have not caused the immediate ground-shift alterations in physics teaching practice that is typical of technology more broadly. While it may be a natural instinct for experimental physicists, physics education researchers, and policymakers to turn to digital technology as the optimistic lynchpins for educational evolvement, the reality is that there are broader considerations to which future PER work on digital technologies would do well to attend.

2.4.2 The future of the digital technologies work of PER and the place of my thesis in it

Keeping in mind this dominant bias toward innovation in the PER work on digital technologies, it is appropriate now to discuss some of the ways which this subset of PER work could evolve in the future. The emergent work of this thesis largely has contended with these future ‘ways’ of doing digital technologies work in PER. Below, I review four considerations that digital technologies researchers might do well to prioritize in future research efforts: namely, (1) studying technology as situated in context, (2) battling the fatigue of technological overpromise, (3) modernizing the expectations for technologies, and (4) deemphasizing summative measures of technology use. As I pose each of these considerations, I also reflect on how the research of this thesis addresses
these scholarly pursuits for the advancement of the digital technologies work of PER.

**Studying technology as situated in context**

First and foremost, future PER work on digital technologies would do well to examine technologies as they are paired with specific teaching methods and embedded within specific learning environments. As it stands now (before any eminent artificial intelligence revolution displaces even the most protected of human thinkers and facilitators), education technologies are designed and implemented by people. Too often in digital technologies work do the technologies get discussed without addressing the contextual factors that influence the function of these tools. As I detailed earlier, this may be due to a bias toward developing and reporting on new technologies rather than explicit research on best practices for existing technologies within a given context.

In this thesis, I explicitly address the relationship between digital technologies and the broader learning environments in which they are embedded. Building on work from Perkins (1991) in Chapter 3, I develop a theoretical perspective for discussing the flexible functions of digital technologies (especially Controllable Worlds). I later build on this theoretical perspective in Chapter 8, after having presenting and synthesizing the research of my five papers, to provide physics educators with potential insights for the ways in which the context around digital technologies can be intentionally altered to encourage specific learning outcomes.

**Battling the fatigue of technological overpromise**

Next, researchers working with digital technologies should be aware of the potential ‘fatigue’ within the PER community around the promise of technology. If somewhat cynical, there may very well be a mounting sense among physics education researchers and physics educators that educational technologies have not lived up to the starry-eyed predictions of their proponents. For instance, CAI work has largely not delivered on its foundational promises of radically reforming physics learning through the efficiency and personalization of programmed instruction. Likewise, CC work has ostensibly not delivered on the utopian promises of discovery learning in technologically-rich learning environments. Except for the extraordinary pressure of the global pandemic pushing teaching and learning toward remote/distance setups (i.e., COVID-19), CSCL work has also largely not delivered on the promises fully-networked education systems and widespread use of MOOCs. The result of these relative shortcomings is that, with the emergence of each new technological offering, the trend has largely been for education researchers to overshoot the promise of the technologies in question. This has almost certainly resulted in the tempering of grand statements around the use of digital technologies in PER and elsewhere, but it may also
lead to a growing divide between those scholars who ‘still believe’ in the potential of educational technology and those whose interests have understandably waned.

A potential (if only partial) remedy to this mounting fatigue may be for future PER work on digital technologies to on the whole spend less time chasing the latest technological breakthrough and spend more time emphasizing and examining technologies that might otherwise feel mundane. In this thesis, an aim of mine has been to not espouse any new digital tool for physics educators as much as I develop more theoretical nuance for future discussions on the use of existing digital tools in the teaching and learning of physics. In doing so, I see the work of this thesis as having potential to the counter the growing fatigue over innovation-obsessed and overpromising technology research more broadly.

Modernizing expectations for technologies
As I will discuss further in the following chapter, many of the digital technologies studied and developed in PER implicitly (or explicitly) value efficient content mastery as the primary learning outcome. In digital technologies research then, there is too often little to no value given to considerations of how digital technologies contribute to the “hidden curriculum” (Redish, 2003, p. 51) aspects of physics teaching and learning that go beyond physics content (i.e., affect, motivation, agency, metacognition, etc.). Unsurprisingly, even the technologies that try to focus on affecting efficient conceptual mastery have meaningful consequences for the implicit messages being sent to students about what it means to do physics, who controls the keys to physics knowledge, and how physics knowledge is organized.

As such, the PER work that deals with digital technologies would do well address the broader impacts of the digital tools used in physics education and modernize the expectations for technologies to foster favorable changes among the ‘hidden curriculum’ variables. In this thesis, I examine how students become motivated through their use of DLEs (see Chapter 5), I explore how students exhibit agency during exploration of DLEs (see Chapter 7), and I suggest how some DLEs may better contribute to a picture of physics as a field of interconnected ideas (see Chapter 3 and 7). Across all of my work, I have valued students using digital technologies in creatively divergent ways, especially without a specific emphasis on efficient content mastery.

Deemphasizing summative measures of technology use
As a continuation of the considerations above, future digital technologies work of PER would do well to deemphasize summative measures of education technology in terms of pre/post shifts in students’ knowledge. In keeping with the tendency for designers and implementors of digital technologies to prioritize efficient conceptual mastery, it is common for the utility of digital technologies to be measured ‘on the whole.’ This type of work tends to portray
digital technologies as *interventions* in physics learning environments. Accordingly, there is a general lack of efforts that examine how physics teachers’ and students’ use of digital technologies actually manifests *in situ*.

In this thesis, I have adopted a methodology inspired by conversation analysis (see Section 4.3) wherein I video record participants’ use of DLEs and analyze the video data in terms of moment-to-moment interactions. In this way, I contribute to the relative lack of research on digital technologies in PER that highlights the diversity and complexity of how students make use of technology. Such an approach allows me to not only develop analytic perspectives for interested physics education researchers, but to also generate recommendations for teachers as they engage with students *while* those students are making use of DLEs.
3 Digital learning environments

My doctoral research has centered on an examination of the function of digital learning environments (DLEs), specifically the subset of digital (educational) technologies which I have come to refer to as ‘Controllable Worlds.’ As such, it is worthwhile in this chapter for me to present an overarching practical taxonomy for my consideration of DLEs and the broader contexts within which DLEs can be situated. Specifically, I make use of and expand upon a previously-published (though to my knowledge, unused) taxonomy of learning environments posited by Perkins (1991) in order to articulate the functions taken on by DLEs like Controllable Worlds. The taxonomy for learning environments presented in this chapter predominantly does not appear in the five papers of this thesis. As outlined in Chapter 1, each of my papers utilizes a perspective particular to the respective analysis found therein and I will come to discuss these paper-specific perspectives in Chapters 5, 6, and 7. Instead, the taxonomy I explain here in Chapter 3 comprises a system for framing the work of all five papers together, crafted for the express purposes of this thesis. As such, in Chapter 8 I will return to the learning environment taxonomy I discuss in this chapter in order to synthesize and generalize across Papers I-V.

The structure of this chapter is as follows. I begin in Section 3.1 by presenting the taxonomy for learning environments as built from Perkins (1991). Thereafter in Section 3.2, I discuss how DLEs such as those studied in this thesis flexibly fit into this taxonomy. In light of my specific focus on Controllable Worlds, I then discuss a productive theoretical criterion of ‘constraints’ in differentiating between DLEs in Section 3.3. Finally, in Sections 3.4 and 3.5, I provide details on the DLEs that I have studied in this thesis—namely, Algodoo and My Solar System (also, the Pendulum Lab)—and the broader circumstances in which I have surrounded those DLEs during my research.

3.1 The anatomy of learning environments

In order to discuss the functions of DLEs within physics education, I make use of Perkins’ (1991) classification of learning environments (both digital and non-digital). Perkins suggests that any learning environment can be divided into five ‘facets’: information banks, symbol pads, construction kits, phenomenaria, and task managers. Each of these facets can be fulfilled by
various media or more often people, but they need not all be present in a given learning environment. Below, I detail each of Perkins’ five facets and provide non-digital and digital examples of educational media, apparatuses, and/or actors that fulfill those facets in many typical physics learning environments. In addition to the five facets that Perkins (1991) outlined, however, I suggest that a useful anatomy of learning environments should also include a sixth facet: *interactional spaces*. My inclusion of this sixth facet stems from my research interest in CSCL as outlined in the previous chapter. After explaining what each of the (now) six facets of learning environments are, I will discuss how certain combinations of these aspects—as constituted by specific media, apparatuses, and actors—form meaningful ‘facet profiles.’

**Facet 1: Information banks**

Perkins defines *information banks* as a facet of learning environments that “[serve] as [sources] of explicit information about topics” (1991, p. 18). Information banks are—to borrow an apt phrase coined for an unrelated purpose (Hooke, 1705; see Singer, 1976)—the “Repositories of Ideas” within a given learning environment. This facet is most commonly fulfilled by a knowledgeable teacher. Historically, the role of *information bank* has also been played by various media formats such as mail in the ‘correspondence courses’ of the 1870s, educational films in the 1910s, radio in the 1920s, and educational television in the 1950s and 60s (Ferster, 2014). More recently, the Internet has proven to be, among other things, the most comprehensive *information bank* of all time.

- Non-digital *information banks* in physics education: textbooks, teachers, worksheets, etc.

**Facet 2: Symbol pads**

The second facet of learning environments identified by Perkins, *symbol pads*, are the parts of learning environments designed for the “construction and manipulation of symbols” (1991, p. 18). In many traditional physics classrooms, students are likely to utilize *symbol pads* such as notebooks or digital tablets while the teacher utilizes *symbol pads* such as a blackboard to supplement the spoken words and gestures of their lecture. In more active/reformed physics classrooms, smaller whiteboards are examples of oft-used *symbol pads* shared between groups of students during collaborative problem solving (e.g., Beichner et al., 2007). In this way, *symbol pads* support students and teachers as they “record ideas, develop outlines, formulate and manipulate equations, and so on” (Perkins, 1991, p. 19), but also function as shared surfaces upon which students can externalize their reasoning in a (semi-)permanent manner.
Facet 3: Construction kits

Construction kits are a facet of learning environments that, similar to symbol pads, act as the locus of construction and manipulation, but construction kits do so for a “fund of prefabricated parts and processes” (Perkins, 1991, p. 19). Construction kits are not altogether common in many physics lecture settings, but electronics laboratories, for instance, that invite students to combine the prefabricated components like resistors and capacitors to explore circuit laws are a common example of construction kits used in physics education. As Perkins (1991) admits, the line between symbol pads and construction kits is indistinct in many cases, but the emphasis of the two facets tends to be slightly different: symbol pads tend to allow students the freedom to write whatever they want while construction kits tend to limit the creative output by imposing a supply of irreducible building blocks.

- Non-digital construction kits in physics education: electronics labs involving prefabricated components, “Maker Spaces,” etc.
- Digital construction kits in physics education: programming languages (especially the ‘higher-level’ ones like Scratch; e.g., Dwyer et al., 2014), Algodoo (see Section 3.4), etc.

Facet 4: Phenomenaria

Perkins defines phenomenaria as a facet of learning environments designed “for the specific purpose of presenting phenomena and making them accessible to scrutiny and manipulation” (1991, p. 19). Phenomenaria are quite common in physics learning environments since physics is an explicit study and modeling of physical phenomena (c.f., ‘pure’ mathematics). Many physics teachers use physical phenomenaria apparatuses for ‘front-of-the-room’ demonstrations (or, perhaps, something more akin to the Observation Experiments of the ISLE approach; see Etkina & Van Heuvelen, 2007), but many simulations used in physics education—such as PhET simulations— can be seen as interactive phenomenaria designed to be manipulated and explored by students directly.

- Non-digital phenomenaria in physics education: demonstration apparatuses, many laboratory setups, etc.
- Digital phenomenaria in physics education: many simulation software such as PhET simulations, Physlets, etc.

Facet 5: Task managers

The fifth facet is task managers, which Perkins defines as those facets of the learning environment that “set tasks to be undertaken in the course of learning,
guide, and sometimes help with the execution of those tasks” (1991, p. 19). *Task managers* most often take the form of physics teachers or structured handouts like the University of Washington Tutorials (McDermott et al., 1998). However, many ‘recitation’ sessions where students come to get more personalized feedback on their understanding of course content and, likewise, some laboratory sessions where students are not following rigid instructions (i.e., non-‘cookbook’ labs) rely less directly on explicit *task managers*. Though somewhat less common in physics education as they might be in teaching more generally, a prime example of digital *task managers* are the so-called intelligent tutor systems that respond to students’ problem solving with individually-tailored feedback.

- Non-digital *task managers* in physics education: teachers, worksheets, tutorials, etc.
- Digital *task managers* in physics education: computer-assisted instruction modules, intelligent tutors, etc.

With the five facets described above, Perkins (1991) establishes a vocabulary for articulating the different aspects that may appear in various learning environments. Nonetheless, while Perkins’ model is a sound foundation for any discussion of the anatomy of learning environments, there is a missing piece from the model that has been all too commonly overlooked and undervalued by the Computer Constructivists of the 1980s and 90s: the role of social interaction in learning. Consequently, I suggest appending Perkins’ five-facet model with an additional sixth facet of learning environments, *interactional spaces*.

*(The missing) Facet 6: Interactional spaces*

*Interactional spaces* are the physical and digital ‘chambers’ that make possible the social interactions of students and teachers. Teaching and learning are often assumptively associated with the physical co-presence of students and teachers in schoolhouses, classrooms, or lecture halls, but setting aside the wide variance in social ramifications each of those spaces entails, such *interactional spaces* are not necessary for teaching and learning. There have long been examples of students independently learning with a total deemphasis on interactional space—such as the ‘correspondence courses’ carried out over mail in the 1870s (Ferster, 2014). In PER, attempts to transform lecture halls into richer interactional spaces can be seen in the research around student response systems (SRSs, see Section 2.3; e.g., Keller et al., 2007), while other efforts such as SCALE-UP have opted to transform interaction spaces by replacing forward-facing rows of desks with circular tables more conducive to student group work (Beichner et al., 2007). Since the advent of the Internet, digital interactional spaces such as chat rooms, forums/discussion boards,
videoconferencing, and even social media have become increasingly prevalent. These digital *interactional spaces* are, indeed, mainstays of many of the distance learning formats in physics education (Rayyan et al., 2014).

- Non-digital *interactional spaces* in physics education: lecture halls, classrooms, labs, study halls, computer labs, etc.
- Digital *interactional spaces* in physics education: discussion boards, learning management systems, email, social media, etc.

The six facets of learning environments explained above provide a good starting point for discussing the design, enactment, and function of learning environments. As I mentioned earlier, it is not necessary for a learning environment to display every one of these six facets. In fact, the real analytic (and pedagogical) power of a taxonomy such as the one given above is in providing a vocabulary for describing the ways that these facets are combined or not combined in various learning environments within which students and teachers might collaborate. Perkins (1991) refers to the particular combination of these facets in a learning environment as the *facet profile* of that learning environment. Some learning environments such as so-called “Maker Spaces” (Price et al., 2016) give emphasis to *construction kits* (including physical materials and/or programming terminals), *symbol pads* (scratch paper and whiteboards) and *interactional spaces*, all while deemphasizing *task managers* such that students largely manage their own progress. Other learning environments such as those that adhere to the ‘traditional’ lecture format rely more heavily on *information banks* (the teacher), *symbol pads* (note-taking surfaces, blackboards), and *task managers* (the teacher, worksheets). As Perkins explains, there are meaningful, implicit pedagogical values in the facet profiles of learning environments:

> A number of premises lie tacit in this profile of facets, for instance, that learning occurs through telling students about things (information banks rather than phenomenaria); that students cannot manage much of their own learning (little task management left to them); and that working out problems rather than constructing entities is primary (symbol pads rather than construction kits).

(1991, p. 19)

Thus, the taxonomy detailed in this chapter arms the interested physics education researcher with a potentially powerful way to distinguish between learning environments and, perhaps more importantly, a means for triangulating the ‘premises that lie tacit’ in learning environments by virtue of the subset of facets on which they tend to rely. By focusing on the implicit foundations of a learning environment as expressed through its facet profile, education researchers can build a more nuanced picture of the contexts in which teaching and learning take place. For the purposes of this thesis, facet profiles allow me to discuss the roles of DLEs, both as intended by designers and also as enacted during actual instances of DLE use.
In the section that follows, I further discuss how the (intended) facet profiles of DLEs interact with the surrounding facet profiles of the broader learning environments in which the DLEs are embedded. The facet profiles of DLEs are, in fact, flexibly responsive to the facet profiles of the broader learning environments surrounding them. Furthermore, though I will not address this point in depth here, it is worth mentioning that the facet profiles of DLEs are also dependent on the students that make use of the DLEs. For example, while Microsoft Word may function as a symbol pad (and perhaps even a construction kit) for an experienced computer user, another user that is hesitant to use the software or is inexperienced with word processors may be unable to make use of the software in the ways it was intended. Thus, the functional facet profile for Microsoft Word as a digital tool should ultimately be judged in situ. For physics education researchers and teachers, this means that it is paramount to observe how students actually make use of a DLE in order to gauge its facet profile. This grounding of digital tools in context has been a core effort of my doctoral work (if not always explicitly expressed through facet profiles).

3.2 The (flexible) facet profiles of DLEs in physics education

In this thesis, I am particularly interested in digital learning environments (DLEs). Following Perkins’ (1991) taxonomy of learning environments involving facet profiles, in this thesis I see DLEs as technologically self-contained learning settings (typically software) that are situated within broader learning environments. DLEs are often employed, or are at least designed to be employed, so as to fulfill some combination of the six facets detailed above. Nonetheless, with the exception of MOOCs and other e-Learning contexts, the DLEs used in physics education are embedded within non-digital learning environments that supplement the function of the DLEs via their own facet profiles. For example, PhET simulations might be coupled with the task manager of a structured tutorial or the feedback of a teaching assistant (e.g., Steinberg, 2000); a programming language might be embedded in an interactional space whereby physics students collaborate on the same code in person—e.g., group-computer interactions (e.g., Obsniuk et al., 2015) and/or so-called ‘pair programming’ (see Goel & Kathuria, 2010, and references therein). Thus, while it can at times be worthwhile to discuss the general characteristics of DLEs in terms of their intended facet profiles, these profiles are necessarily flexible in response to the broader learning contexts in which they are rooted.

In the case of an ‘intelligent tutor’ DLE, where a user is guided through a series of adaptive questions tailored to how well they perform on previous
questions, the DLE is generally intended to have the facet profile of *information bank + task manager* (e.g., Schulze et al., 2000). Alternatively, interactive video-enhanced tutorials (Maries et al., 2020) are often intended to have a facet profile of *information bank + task manager* interspersed with *phenomenaria* in the form of embedded simulations. Still, by embedding these DLEs and any others in various broader learning environment contexts, their functional facet profiles may change. That is to say, the facet profiles of DLEs are *context dependent*. An intelligent tutor DLE could be utilized at home by a single student or, conversely, in a recitation setting among a group of students sharing the same device. Between these implementations of the DLE, the *interactional space* of the DLE has changed and, thus, the functional facet profile of the DLE may change as a consequence. In the group setting, control of the intelligent tutor must be negotiated amongst the group members so we might expect to see some of the *task manager* facet shift from the DLE to the students themselves. Though the intelligent tutor DLE will likely still contribute to the same facets as before, the nature and extent of the DLE’s *task manager* facet has been altered. Due to this shifting, contextually-dependent nature of DLEs’ facet profiles, it becomes less useful to define the facet profile of a certain DLE in isolation, and more useful to discuss the *range* of potential facet profiles that might emerge from students’ use of that DLE in given learning contexts. Alternatively, it can be useful to discuss and intentionally facilitate changes in the broader context surrounding DLEs in order to tailor the functional facet profiles of DLEs.

In this thesis I have looked at how students make use of a certain category of DLE, namely those DLEs I referred to in Chapter 2 as Controllable Worlds like PhET simulations and microworlds. However, while it is commonplace in PER and science education research to refer to these DLEs with the label ‘simulation’ or ‘microworld’ as if those things are fixed, a richer appreciation of these DLEs comes from examining their intended facet profiles and enacted facet profiles they take on in various contexts. Software that might be labelled as ‘microworlds’ may typically take on the role of *construction kit*, but when specific pre-fabricated constructions are given to students within these microworlds, those same DLEs can take on more of the characteristics of *phenomenaria*. In his discussion of microworlds, Rieber (1996) suggests that a DLE can be regarded as a microworld if it is observed to act 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 Reiber, a DLE should, therefore, be judged to be a microworld in its specific use within a particular context. It is precisely this context dependent perspective on microworlds (and DLEs more generally) that I use throughout this thesis.

Especially when you consider the context dependency of DLEs’ facet profiles, it becomes apparent that there is some continuity between what researchers often refer to as ‘simulations’ and ‘microworlds’: simulations may be able to be embedded in broader learning contexts that result in students using them in a manner more akin to the construction kit facet of microworlds, while vice versa, microworlds might be embedded in contexts that result in students using them in a manner more akin to the phenomenaria facet of simulations. In my work, I have chosen to define this continuum that separates simulations and microworlds in terms of constraints. To be more precise, I describe construction-kit-functioning DLEs as “less-constrained” and phenomenaria-functioning DLEs as “constrained.” I will discuss the foundations of my constraints-based view of Controllable Worlds below.

Before I do so, however, it is worth a brief aside about the relationship between the intended facet profiles of microworlds and programming environments, both of which can function as construction kits. In fact, as with microworlds and simulations, there is a continuity (albeit along a different continuum) between microworld-functioning DLEs and programming environments. I need not deliberate the details of this distinction here—as programming environments are not a focus of the research papers presented in this thesis—but suffice it to say that I propose that microworlds lie on a continuum with programming environments defined by the degree to which those environments function as semi-formalisms (see Chapter 5 for further discussion of this term). The relationship between programming and the microworld-functioning DLE, Algodoo, is taken up briefly in Section 5.3, but a more thorough reflection on the continuum between these types of DLEs is found in Chapter 8. For now, in setting up my attention to Controllable Worlds that constitutes the focus of this thesis, it is apropos to limit my discussion to the continuum I have defined for differentiating between construction-kit-functioning DLEs and phenomenaria-functioning DLEs in terms of constraints.

3.3 The ‘constraints’ view of Controllable Worlds

As I alluded to in Section 2.3, many of the Controllable Worlds utilized in and developed for physics education—such as PhET simulations (Wieman, Adams, et al., 2008) Physlets (Christian & Belloni, 2001) and QuVis animations (Kohnle et al., 2012)—tend to be centered on particular physics phenomena and/or concepts. These phenomenon-specific Controllable Worlds function for students as well-defined arenas of attention: that is, in the words of
their designers, these DLEs are “specifically designed to productively constrain students’ focus on the aspects experts believe are most important” (Wieman, Adams, et al., 2008, p. 395) for a given phenomenon or context. I refer to the Controllable Worlds that take this approach as *constrained DLEs*. Many, but not all, constrained DLEs function as *phenomenaria* in their facet profiles. In doing so, these constrained DLEs implicitly conform to what researcher Manu Kapur calls the “deeply ingrained maxim” in education research literature that students require significant, externally-imposed constraints to avoid failure during problem solving (Kapur, 2008, p. 382).

However, some education research scholars have questioned the “overemphasis on efficiency” (D. Schwartz, Bransford, & Sears, 2005, p. 34) implicit in some of the types of learning environments that present students with all of the ‘necessary’ aspects of a context up front. The pursuit of efficient conceptual mastery of physics in constrained DLEs might inadvertently mean that students do not get the opportunity to engage in some of the ‘messier’ aspects of doing physics (Bryan, 2006; Chinn & Malhotra, 2002), do not have the room to exercise innovation during problem-solving (D. Schwartz et al., 2005), or do not falter in ways that may be beneficial to learning in the longer term (Kapur, 2008; Kapur & Kinzer, 2009). Beyond this, the imposed structure of constrained DLEs may inhibit desirable learning goals in physics education such as students developing an interconnected view of physics and/or students exercising agency through the creative pursuit of their own lines of reasoning.

In the majority of this thesis (though not exclusively; c.f., the third and fourth datasets, discussed in Section 4.2), I have examined participants’ use of a different kind of DLE—namely, the physics software, *Algodoo*—which is not designed to provide students with access to a single specific phenomenon. That is, it is less-constrained in its design than the DLEs typically used in physics education. I refer to the DLEs that are not centered on a specific phenomenon or set of phenomena as *less-constrained DLEs*. These DLEs often function as *construction kits* in their facet profile. As relayed in my discussion of my research journey (Section 1.1), my initial motivation for studying the ‘less-constrained’ *Algodoo* in Papers I and II stemmed, in part, from the fact that it represented an under-researched digital technology in PER when compared to the literature base on the more typically implemented, ‘constrained’ simulation software. I also study to *Algodoo* in Papers IV and V, since my exploration of case study data ultimately led to me finding an interesting interplay between a responsive teaching approach and the structure of the less-constrained *Algodoo*. In Paper III, however, I have examined a pair of participants’ embodied dance around the constrained PhET simulation, *My Solar System*. It is important to recall that both of these DLEs—*Algodoo* and *My Solar System*—fall under the description of Controllable Worlds. In my utilization of both less-constrained and constrained DLEs in this thesis, then,
it is pertinent for me to discuss in greater detail the prevailing philosophy behind physics DLEs based on constraints as found in the existing PER literature.

The prevailing philosophy behind DLEs in PER and an alternative offered by less-constrained DLEs

A predominant precept in the design and implementation of DLEs for the teaching and learning of physics is the notion of productive constraints (W. Adams, Paulson, et al., 2008; Christian et al., 2015; Finkelstein, W. Adams, et al., 2005; Podolefsky et al., 2010; Roth, 1995; Roth et al., 1996; Wieman et al., 2008). Such work borrows from Gibson’s (1977) framing of *affordances* and *constraints* in learning environments. Affordances can be thought of as the possible and productive actions to be carried out with a tool, as perceived by the user. Constraints, on the other hand, “restrict the actions that a user can take” (Podolefsky et al., 2010, p. 3). Thus, in using the term constrained DLEs within this thesis, I refer to those learning environments that intentionally restrict the actions that students can take in the exploration of particular phenomena.

(Productively-)constrained DLEs are each focused around a specific phenomenon (or small set of phenomena) such that students are granted intentionally-delimited control over a collection of variables that pertain to said phenomenon. For example, the *Wave Interference* simulation (PhET Interactive Simulations, 2020) centers on interference phenomena in an interactive ‘wave pool,’ affording users control over the frequency and amplitude of waves as well as the separation between wave sources and separation/width of slits in a movable screen (see Podolefsky et al., 2010). The frequency slider in this simulation is purposefully constrained to the range of frequencies “that are pedagogically useful for exploring interference phenomena” and a maximum of two sources and two slits are allowed, since any more “would be difficult for students to interpret” (Podolefsky et al., 2010, p. 10). The rationale given in the PER literature asserts that constrained DLEs improve physics students’ conceptual mastery (seen in, for example, Finkelstein et al., 2005; Keller et al., 2006; Zacharia & Anderson, 2003) due to the manner in which those environments provide students with, and direct students’ attention toward, the relevant features for each physics scenario. In a related manner, constrained DLEs have also been shown to support students’ productivity during self-guided exploration16 (W. Adams, Paulson, et al., 2008; Podolefsky et al., 2010). Results such as these lend credence to the argument that physics students need sufficient scaffolding during exploratory activities so as to prevent them from “creating situations which are unnecessarily complicated or distracting” (Podolefsky et al., 2010, p. 10; see also the related discussion on the

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16 In the context of Podolefsky et al. (2010), “productive exploration” referred to students remaining engaged in sensemaking and seeking answers for their own questions within DLEs.
necessity of imposed structures during learning in Kirschner et al., 2006; Sweller et al., 2007). Aside from the theoretical arguments for the use of constrained DLEs in the PER literature, the extensive utilization of these DLEs in physics education likely stems from the pressures put on physics teachers to efficiently teach large numbers of students and/or manage limited sets of resources.

Though constrained DLEs may promote physics students’ conceptual understanding, there exist other potential learning goals for physics students that may not be promoted by the constrained nature of these DLEs. For one, since many students come to view physics as a fragmented field of weakly-connected facts (Bagno et al., 2000; Elby, 2001; Hammer, 1994), physics educators may want to encourage students to work fluently across and between content areas to help constitute a more topically-interconnected picture of physics knowledge. Constrained DLEs effectively isolate each physics phenomenon into distinct environments, so they may have the effect of contributing to students’ siloing of physics knowledge into separate thematic areas. Another objective in many modern science classrooms is, increasingly, for students to explore their own lines of inquiry in creative/innovative ways (Mishra & The Deep-Play Research Group, 2012; Newton & Newton, 2014; D. Schwartz et al., 2005). Here again, by acknowledging that constrained DLEs purposely limit the possible outcomes that students can explore (so as to not be ‘distracting’), it is reasonable that these environments could end up curtailing opportunities for students to exercise their creativity. For instance, physics teachers may want students to work in environments where they can construct their own testing experiments (Etkina et al., 2019), make conceptual detours, discover the relevance of scientific variables for themselves, and even productively fail (Kapur, 2008; Kapur & Kinzer, 2009). This constrained view is especially taken up in the discussion of Chapter 7.

In light of these possible drawbacks to constrained DLEs, I have been notably motivated in the work of my thesis to explore the potential utility of the less-constrained DLE, Algodoo. In the section that follows, I present some details of the Algodoo software, as well as the details of another DLE which my work has featured, the PhET simulation My Solar System.

3.4 The DLEs I have studied

As mentioned above, the research in this thesis has centered on investigating students’ use of two Controllable Worlds in particular: namely, a software called Algodoo and the PhET simulation My Solar System. I have also collected data (see Section 4.2.4) with the PhET simulation, Pendulum Lab, but this data was ultimately never used in any of my publications. Algodoo, which has been the DLE in focus for Papers I, II, IV, and V, was observed in my data to function as a less-constrained construction kit. My Solar System, which was
utilized by the students analyzed in Paper III, tended to function more as a constrained *phenomenarium* in the data collected. Having provided the theoretical background of DLEs in the preceding sections of this chapter, I now provide some specifics about these DLEs which have featured in my doctoral thesis research.

3.4.1 *Algodoo* II

*Algodoo* is a two-dimensional DLE which was inspired, at least in part, by Seymour Papert’s constructivist 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) (Figure 2).

![Figure 2. A screenshot of a simple Algodoo scene.](image)

When users create scenes of objects within *Algodoo* and press the play button, the scenes they have built then ‘play out’ in accordance with two-dimensional
Newtonian mechanics. In the data collected for this thesis, *Algodoo* has appeared to function as a less-constrained DLE for participants during physics problem solving and free exploration. As such, I will refer to *Algodoo* throughout this thesis as a ‘less-constrained DLE’ rather than constantly acknowledging that, more appropriately, *Algodoo* appears to consistently function as a less-constrained DLE for the participants in my data.

While *Algodoo* allows users to model various phenomena and machines, unlike other mathematics programming modeling tools used in physics education 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 uneditability of *Algodoo* 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 *Algodoo* retains a level of algorithmic semi-transparency that allows students to create and manipulate virtual worlds without requiring that they have prior knowledge of programming. In this latter sense, *Algodoo* 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 *Algodoo* 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; Gregorcic & Haglund, 2018). The relationship between less-constrained, microworld-like DLEs like *Algodoo* and programming is discussed further in Chapter 8.

Another important characteristic of *Algodoo* 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 *Algodoo*’s capability for representing mathematical concepts.

*Representations afforded by Algodoo*

*Algodoo*, 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). *Algodoo* 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.\(^{17}\) Nonetheless, while including these mathematical aspects, the Algodoo 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.

![Figure 3. Examples of the representations provided by Algodoo, namely the ‘Velocities’ tab for a polygon (left) and a graph from the ‘Show Plot’ function for a box (right) (reproduced from Paper II with permission from Springer Nature).](image)

As I discuss in Papers I and II, by including mathematical representations (see Figure 3) 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, Algodoo superimposes formal physics and mathematical ideas onto a more familiar world of physical, albeit simulated, interactions. Algodoo 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 Algodoo’s overlay of dynamically-changing

\(^{17}\) Note here that the capability to generate dynamic representations is a powerful characteristic of Algodoo 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.
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.

3.4.2 My Solar System III

![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. 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 (reproduced from Paper III under the CC BY 4.0 license).](image)

*Figure 4. 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. 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 (reproduced from Paper III under the CC BY 4.0 license).*

*My Solar System* is a two-dimensional simulation software from PhET which allows users to create circular bodies of varying masses, give them initial velocities, and observe how the created systems behave (Figure 4). In contrast to *Algodoo*—which allows for more dynamic touch-screen inputs and, due to its less-constrained nature, the creation of a wider variety of user-created objects—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 4.2.3), in part, to examine how its preset-based, constrained structure differed from the less-constrained 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.

### 3.4.3 Pendulum Lab

It is worth briefly mentioning a third Controllable World that featured during my doctoral studies, but which is not present in any of the analyses in this thesis: the *Pendulum Lab* PhET simulation. For the purposes of this thesis, it is really only important to know that the *Pendulum Lab* is also a two-dimensional PhET simulation (like *My Solar System*) that allows users to carry out virtual experiments with pendula. I collected data around students’ use of the *Pendulum Lab* as part of the fourth dataset (Section 4.2.4), but ultimately ended up focusing on a different portion of that dataset for Paper V. As such, I only mention this DLE here for completeness and for clarity when discussing my data collection.

### 3.5 The contextual factors within which these DLEs were implemented in my research

As detailed earlier in this chapter in my discussion of the flexible facet profiles of DLEs (Section 3.2), I argue in this thesis that it is important to consider the broader learning environment contexts within which DLEs are used. In this final section of this chapter, I detail the four most salient contextual factors that I believe shaped how students used the DLEs in my data. The first two of which, an interactive whiteboard and isolated group work, are situational factors that mostly affected the interactional spaces of the learning environments in my data. The third and fourth contextual factors, the prompts given to participants and the researcher(s) in the room, have more to do with the task managers of the learning environments in my data. Each of these broader contextual features is dealt with further in the next chapter within the discussion on data collection (Section 4.2), but it useful here to reflect on how these features of the learning environment affected the function of the DLEs situated within them.
3.5.1 The interactive whiteboard 

The first component of the learning environment that shaped the interactional space facet for the participants in my thesis was an interactive whiteboard (IWB). 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 IWB (Gregorcic, 2015a). The IWB provides students with common perceptual ground (Roth & Lawless, 2002a) that 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; see also, the related discussion in Section 4.3). 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). In this way, the IWB tends to make the interactions of participants more embodied or, implicitly, makes the DLE running on the IWB more readily related to their bodily experience (see also, Gregorcic & Haglund, 2018).

Students’ increased bodily activity in the presence of large touchscreens should perhaps not come as a surprise. Students often perform in a manner that matches the size, nature, and purpose of the surfaces on which they work. For instance, teachers can expect students to make small, nearly-imperceptible movements as they scribble down tiny notes on their ‘crib sheets’ for exams. Likewise, teachers can expect (and encourage) students to scale up their movements while composing a ‘mind map’ on a whiteboard in small groups. In the case of large touchscreens like the IWB, the interface requires students to reach across the screen and press, swipe, and drag with their actual hands. The nature of the IWB itself compels bodily activation. 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.

3.5.2 Small groups of participants in isolation

The second salient aspect of the learning environments surrounding the DLEs used in this thesis comes from the choice to video record the participants in isolated groups of two to three at a time. The decision for the groups to be isolated was made for logistical reasons: the PER group at Uppsala University has exclusive access to a small conference room outfitted with a single IWB. This meant that a single group of participants could be studied at length in this conference room without interruption. Small groups were chosen for the data
collection in order to encourage the students to ‘think aloud’ rather than work in silence (Charters, 2003).

The reasons for my use of small groups notwithstanding, this arrangement undoubtedly impacted the ways the DLEs were used in my data. First, the benefits of working in groups has been reported in the PER literature (e.g., C. Singh, 2005). Beyond this, however, in a manner similar to IWB discussed above, the addition of a participant collaborator during the sessions appeared to encourage more embodied meaning-making in the data I collected. The participants employed gestures to communicate to one another and the researchers in the room. With the case studied in Paper III (Chapter 6), the participants directly engaged with one another in an embodied dance. Thus, it seems apparent that the context of small groups surrounding the DLEs also worked to shape the interactional space of the learning environments such that the students were encouraged toward embodied meaning-making and bodily engagement during problem solving.

3.5.3 The prompts given to students

The third aspect of the broader learning environment worth mentioning is the nature of the tasks given to the students. A consistent feature across all of the datasets collected in this thesis was open-ended prompts. For the purposes of this thesis, open-ended prompts are those designed to encourage “activities in which students have greater autonomy in what and how physical phenomena are investigated, rather than simply following instructions” (Wilcox & Lewandowski, 2016, p. 1). As will be discussed in detail in Section 4.2, each data collection session began by giving the participants up to an hour to ‘simply explore’ and get used to the DLE in question. Following this first period of exploration with the DLE, the participants were then given an open-ended prompt centered around a certain physics phenomenon (e.g., a puck rolling down a ramp, the orbital motion of astronomical bodies, pendulum motion). In every case, these prompts were given to the participants orally rather than in writing. The reasoning for using open-ended prompts in the data collection sessions stemmed from my desire to see how the participants would go about using the DLEs without a predetermined scaffold of activities. In fact, some of the richest data I collected came during the initial exploratory phase of my data collection sessions, which were the sections of my data where the participants had the most autonomy. The data from these portions of the sessions features in three of the five papers in this thesis (Papers II, IV, and V).

The open-ended nature of the prompts primarily influenced the task manager facet of the learning environments. Whereas many physics learning environments have explicit task managers in the form of teachers, laboratory assistants, or structured tutorials, the lack of such an overt task manager en-
couraged the participants in my data to utilize non-disciplinary meaning-making resources (see Chapter 6) and implicitly signaled to the students that their divergent thinking was worthwhile. In fact, there is some evidence that open-ended physics activities may improve students’ affect and confidence when performing physics experiments as compared with traditional laboratory exercises (Wilcox & Lewandowski, 2016). In this way, more informal learning was encouraged through the limiting of task managers in the learning environment (see Section 5.2.1). It is important to note, however, that the students were never engaged in completely free exploration since there was a researcher in the room offering support.

3.5.4 The researcher(s) in the room

The fourth and final salient aspect of the learning environment surrounding the DLEs in my data is the researcher(s) in the room. In each of the data collection sessions of this thesis, the participants worked in isolated small groups, with open-ended prompts, and with a single researcher or pair of researchers present to offer guidance. The intention was for the researcher(s) to help the participants if they needed help with particularities of the DLEs and/or to encourage the participants to externalize their thinking for the video recording when things went otherwise unspoken between the participants.

As with the open-ended prompts, the researcher(s) in the room again had the most direct impact on the task managers facet of the learning environments. While it was not intended for the researcher(s) to offer any specific kind of guidance to the participants other than the loose goals mentioned above, I found that the researcher(s) instinctively enacted many effective teaching techniques that paired particularly well with less-constrained DLEs and open-ended prompts. This became the focus of Paper IV and the basis for my attention on responsive teaching (Robertson et al., 2015a; taken up in more detail in Chapter 7). In this way, the researcher(s) acted as variable task managers in the learning environment, responding to the participants’ actions and interactions in a manner that pushed them in a disciplinary direction.

3.6 A summative note on digital learning environments

In this chapter, I have presented and expanded upon Perkins’ (1991) view of learning environments in terms of six facets: information banks, symbol pads, construction kits, phenomenaria, task managers, and interactional spaces. Metaphorically speaking, these six facets can be thought of as the palette of colors from which teachers can compose learning environments. I have furthermore argued in this chapter for a view of DLEs that focuses on the flexible facets profiles those DLEs take on in the context of their broader learning environment surroundings. From this perspective, it is important to observe how
DLEs are used by particular students in particular settings in order to determine how those DLEs function. The facets-based picture of learning environments I have presented in this chapter is useful for differentiating between types of DLEs and for better identifying the role of DLEs amidst the contextual factors in which they are embedded.
In Chapter 2, I reviewed the relevant PER work on digital technologies and determined that among other things, there is a lack PER work that focuses on the moment-to-moment evolution of students’ use of DLEs and/or work that examines how DLEs may help physics educators meet modern goals for the physics classroom. In Chapter 3, by discussing the flexible function that DLEs may take within broader learning environments, I motivated the need for research that leaves open the possibility for DLEs to be used by students in divergent, unexpected ways. Now in this chapter, I discuss how a case-oriented methodology allows me to take these factors into consideration, while also allowing me to address my research questions set out in Chapter 1.

To begin, in Section 4.1 I discuss the nature of case-oriented research. Then, I detail the methods used to collect the four datasets that comprise the data of this thesis (Section 4.2) and elaborate on the general analytic approach I have taken inspired by conversation analysis (Section 4.3). This includes a discussion of the ‘embodied turn’ that has occurred in the research on language and social interaction (Section 4.3.1) and some details about the ways I have chosen to represent my data in publications with multimodal transcripts (Section 4.3.2). In Section 4.4, I conclude this chapter with a discussion of trustworthiness and ethical considerations. It is important to note that, in conjunction with the perspectives that feature within the five papers of this thesis, the theoretical considerations surrounding case-oriented research as well as my general analytic approach inspired by conversation analysis and the accompanying theoretical considerations are used across Chapters 5, 6, and 7.

4.1 Case-oriented research

This 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 and answers. Drawing on the work of Greene and Caracelli (1997), Robertson et al. (2018) explain how PER can be viewed in terms of two methodological camps, namely case-oriented research and recurrence-
oriented research. The names of these camps 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] 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 differently. 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 (Hake, 2000). Indeed, some researchers within PER and elsewhere often identify themselves first and foremost by their answer to the ‘qualitative/quantitative’ question.19 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.

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19 Recently, the zealotry of this methodological debate may have subsided somewhat (see Robson & McCartan (2016) and Russ and Odden (2018) for a discussion of alternatives for identifying one’s research in the space of PER).
In this thesis, I have been particularly interested in exploring the socially-negotiated meaning making of students as they utilize less-constrained DLEs in the context of open-ended prompts. As discussed in Chapter 2, this is a topic which has yet to receive significant attention in PER. As such, I see the area of research I have engaged with 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. 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 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 students’ use of DLEs as in 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 continuing to pose quantitative questions around students’ use of digital tools in the process of physics learning. The case-oriented methodological perspective is apt for developing theory and aligned with my tracking of moment-to-moment interactions within novel learning environments. As such, 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 five papers that make up this thesis. The data comprises four datasets in the form of video-recorded case studies, each one involving small participant groups interacting around a Controllable World. In what follows, I will discuss how the participants of the studies were recruited, the tasks that the participants were given, and the equipment that was used to carry out the data collection.

The first dataset was collected as my initial foray into the functionality of Algodoo in relation to the physical world (as per Research Question 1). Based on the richness of the participants’ interactions, I was compelled to use this dataset for Papers I, II, IV, and V, the first two of which now comprise the work for Theme 1 of this thesis (Chapter 5). The second dataset was collected before my doctoral studies began, as part of my supervisor’s (Bor Gregorcic’s) doctoral thesis work in Slovenia. I will review the details of the data collection as reported by Gregorcic in his thesis and associated publications. This second dataset was adopted for use in this thesis as it was found to include a multi-modally-rich case that furthered the theoretical discussion of Paper II. The third dataset was collected as part of a master’s thesis which I co-supervised with Gregorcic and which is used in Theme 2 (Chapter 6). Though I did not physically participate in the data collection sessions for the third dataset, the methods used by Elmer Rådahl were designed after, among other things, my experience gained from the collection of the first dataset. It was this third dataset that inspired me to take up the embodiment focus of Research Question 2. The fourth and final dataset was collected by me during a research visit abroad at the University of Colorado Boulder. This fourth dataset was originally collected with the intention of comparing participants’ use of a less-constrained DLE like Algodoo with a constrained PhET simulation. However, for the purposes of Paper V, ultimately only the Algodoo portions from this were used, contributing to the teacher-directed analyses at the core of Theme 3 (Chapter 7). Some pertinent details about the four datasets—i.e., the papers in which they were used, the research questions they helped answer, the Controllable World software studied, and the language in which the data collection sessions were held—is summarized in Table 4 (next page).

4.2.1 The first dataset I & II

In my initial data collection, I was interested in exploring how less-constrained DLEs might be used by students in relation to the physical world. Thus, for the first dataset, video recordings of participant 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 participants—who volunteered to partake in this study—were completing their first semester of physics and mathematics. I encouraged the participants to sign up with another participant with whom they were comfortable working, such that the pairs of participants were self-organized. This particular demographic of participants was selected because I anticipated the participants’ 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).

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Used in</th>
<th>Themes</th>
<th>Controllable World studied</th>
<th>Original Language</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Paper I, II, IV, &amp; V</td>
<td>1 &amp; 3</td>
<td>Algodoo</td>
<td>English</td>
</tr>
<tr>
<td>2</td>
<td>Paper II</td>
<td>1</td>
<td>Algodoo</td>
<td>Slovenian</td>
</tr>
<tr>
<td>3</td>
<td>Paper III</td>
<td>2</td>
<td>My Solar System</td>
<td>Swedish</td>
</tr>
<tr>
<td>4</td>
<td>Paper V</td>
<td>3</td>
<td>Algodoo</td>
<td>English</td>
</tr>
</tbody>
</table>

Figure 5. The physical ramp setup used alongside Algodoo in the first dataset, labelled with the relevant height and distance from the prompt given to the participants.

The data collection took place in small room equipped with an IWB (running Algodoo) and a physical ramp positioned on some nearby tables. The physical ramp setup (Figure 5) 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 parts: (1) a 45-minute\textsuperscript{20} 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 all three parts of each session, the data used in Paper IV and V came from the first, 45-minute portion of the data collection. 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:

\textit{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.}

Throughout the sessions for the first dataset, 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 to encourage the participants to utilize both Algodoo and the physical ramp setup to convince us of their result. Although Swedish was the participants’ native language, the participants were asked to use English during the session so that I could follow along and respond to their interaction when helpful. See Section 4.4 for a discussion of languages and translation.

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 participants 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 dataset

As mentioned at the start of Section 4.2, the second set of video data was collected previous to the start of my doctoral studies by Bor Gregorcic as part of his doctoral thesis (2015b). The goal of Gregorcic’s thesis 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). The data were collected a Slovenian high school where a transition to school-wide use of

\textsuperscript{20} All durations are approximate and varied slightly for each pair of participants.
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 portion of data which I have utilized from this study (the second dataset of my 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 Algodoo-IWB setup to explore celestial motion. The students were presented a scene in Algodoo that 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 Algodoo to provide students with “hands-on [access] to [the] otherwise experimentally inaccessible topic” of orbital mechanics (Gregorcic, 2015a, p. 515). The students used the Algodoo-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 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 dataset 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 dataset III

The video data comprising the third dataset were initially collected as part of a master’s thesis project in PER (Rådahl, 2017). The project investigated when and how responsive teaching approaches (Robertson et al., 2015) might be effectively applied during open-ended prompts involving small groups of students in digitally-rich environments. Six participants were recruited from a class of Swedish senior-level high schoolers, all of whom were enrolled in a three-year natural science program. This particular class of students was chosen on the basis that Rådahl (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. 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 participants 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 (in the same room that the first dataset 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 DLEs by the researcher.

21 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.
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. 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 participants were stuck, encouraging them to go further with interesting discussions, and occasionally requesting clarification from the participants 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 participants being the only ones present in the room, the video sources were backed-up with an audio recording from a smartphone placed face-down on a table near the participants.

4.2.4 The fourth dataset

The fourth and final set of video data were collected during a research visit of mine to my undergraduate alma mater, the University of Colorado Boulder (CU Boulder), during the fall semester of 2017. The aim was for me to collect data on how students used Algodoo, a less-constrained software, as compared with a more typically-used PhET simulation. As mentioned in Section 2.3, the team of researchers developing and researching PhET simulations is housed at CU Boulder in close collaboration with the PER group. As such, we thought that CU Boulder would be an ideal setting for me to examine the relationship between Algodoo and PhET simulations among a community of researchers and educators who have expertise implementing the latter software.

I decided to compare how physics students in their first semester of (undergraduate) physics at university level would deal with pendula phenomena with Algodoo and the PhET simulation, Pendulum Lab. Participants were encouraged to volunteer from a large-enrollment (N ~300-600) introductory physics class via an email sent from their course-responsible teacher as well as via a slide advertising the study shown at the beginning of one of the lectures. Participants who volunteered were randomly assigned to either work with Algodoo or the Pendulum Lab simulation with a partner. In the end, there were four Algodoo groups and only two Pendulum Lab groups. As with the first and third datasets, the sessions comprised three parts: (1) a 30-45-minute-long exploration of the DLE (either Algodoo or the Pendulum Lab simulation) without a specific prompt, (2) a 45-minute-long task concerning pendulum

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22 CU Boulder was chosen due to my continued relationship with the PER group there, especially with Noah Finkelstein, that had been cultivated during my work on my undergraduate honors thesis in PER (Euler, 2015).
motion, and (3) a short wrap-up interview with a few questions about the experience. The task given to the participants in second part of the sessions was the same regardless of the DLE they were using: namely, the participants were asked the following,

*Using this software, explore and determine the physical characteristics of a pendulum that dictate its period. Whenever possible, come up with a mathematical relationship using a proportion or equation.*

Throughout the sessions, similar to the first dataset, I sat in the room with the participants to play the role of a skeptic observer. Again, I encouraged the participants to elaborate on their reasoning or explain what they had just done.

Similar to the other three datasets, each pair of participants was video recorded in a small, otherwise-vacant room. However, while every other dataset made use of a DLE running on an IWB, a lack of IWBs at the CU Boulder Physics Department required a different interface during the collection of the fourth dataset. Instead of an IWB, the participants were given a laptop running *Algodoo* that was then projected onto a screen in front of them. The hope with including the projector alongside the laptop was that participants might be encouraged to get up and gesture around the larger image on the screen in a manner similar to what we had observed when participants made use of a DLE on the IWB. However, all of the participating groups remained seated in front of the laptop during these sessions, so it is unclear if the projected image from the laptop screen influenced the participants’ use of the DLEs. As mentioned in Section 3.4.3, the data collected with the *Pendulum Lab* simulation were ultimately not used in this thesis. Instead, Paper V makes use of the four sessions where the pairs of participants used *Algodoo*, specifically the first, free-exploration portions of those four sessions where the participants familiarized themselves with the *Algodoo* software.

The data collection sessions consisted of two cameras and a screen capture recording from the laptop. The first of these cameras was placed in front of the participants on the table with the laptop in order to record the faces and torsos of the participants as they used the laptop. The second camera was placed behind the participants, framed in such a manner as to record the participants’ backs and projected image of the laptop on the screen.

### 4.3 My general analytic approach

With the exception of Paper V, the analytic approach used across the papers of this thesis is generally one that is inspired by *multimodal conversation analysis*. Conversation-analytic approaches tend to involve the fine-grained study

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23 I will address the methodological commitments of Paper V in Section 7.2.1 within my discussion of Theme 3.
of human interactions on a moment-to-moment basis. 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, body posture, etc. The conversation analysts’ attention to the temporal sequencing of meaning-making resources, especially when combined with a consideration for the multimodality of interactions, allows for the examination of the interplay of talk, gesture, gaze, body position, etc. as they are employed by interlocutors to negotiate meaning. For example, Goodwin (2003, 2007) used conversation analysis to examine how archaeologists use gestures closely linked to their setting—which he calls environmentally-coupled (or symbiotic) gestures—alongside talk to communicate within a dig site. In multimodal conversation analysis, gesture, gaze, and body positioning are considered in concert with 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 variety of the ways that humans communicate—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 meaning-making resources, along with the methodological practices of close analysis and transcription of video footage, that I find useful for this thesis.

The specifics of the analytic approaches carried out in each of the papers of this thesis differ slightly from one another, especially as a consequence of each paper employing different perspectives in order to focus on distinct aspects of participants’ interaction with and around DLEs. Thus, while I have maintained a consistent analytic attention to participants’ moment-to-moment multimodal interactions in the first four papers of this thesis, the specifics of analysis for each paper are dealt with in the respective chapters to follow (in Chapters 5, 6, and 7). In the next section, I provide some relevant background for the fields of research from where I have drawn my conversation-analytic methodological inspiration: namely, the increasingly multimodal research on language and social interaction (LSI) from linguistic and sociological/anthropological perspectives. Thereafter, I review my use of multimodal transcriptions and line illustrations for the presentation of data.

24 By haptic-touch, I 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 my discussion of Human Computer Interfaces: Touchscreens and Haptics in Section 2.3).
4.3.1 Background on research on language and social interaction: the ‘embodied’ turn

In this section, I review how the field of research on language and social interaction (LSI) developed multimodal focuses within the 20th century. In particular, I highlight how the traditions of linguistics and interactionist sociology/anthropology have both come to value *embodied* forms of meaning making alongside talk and written text. In his review of the field of LSI, Maurice Neville (2015) discusses this point in terms of 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). Neville 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 briefly 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 research**

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 ways the signs involved the individuals who interpreted them.25 The bodies of work produced by these scholars 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 Volośinov had developed a Marxist-inspired theory in response to Saussure which aimed at contextualizing semiotics within social processes (Volośinov, 1930). For Volośinov, any meaningful study of language could not ignore the social context within which language occurred. Another scholar, the English linguist

25 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).
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 linguistics (SFL). This was a theory that posited the necessary criteria, 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 explicitly 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, 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.26 The list of researchers at the Newtown Semiotic Circle included Gunther Kress, Robert Hodge, Theo van Leeuwen, Jim Martin, Paul Thibault, and Terry Threadgold. Through their collaborations, these researchers would go on to found the field of social semiotics (Jewitt et al., 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 the 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 the written and spoken forms of communication to include a focus on 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 at 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 within linguistics also began embracing the label of multimodality (Kress, 2010). 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

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26 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.
of interaction and multimodality in the 2000s encouraged linguists to analyti-
cally appreciate embodiment among other things in their research.

**Embodiment in the sociological/anthropological tradition of LSI research**

The related fields of sociology and anthropology arrived at a focus on embod-
iment and multimodality by an altogether separate route from linguists. In the
1960s, researchers from a background in sociology/anthropology had already
taken up the study of social 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 estab-
lish a “distinct theoretical and methodological approach to the study of social
interaction” (Jewitt et al., 2016, p. 86), which we now call *conversation anal-
ysis*. 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 of conversations as a means for demonstrating the prevalence of
‘adjacency pairs’ in conversational turn-taking.

By the 1970s, scholars such as Charles Goodwin began to use *video* re-
cordings as the data for conversation analysis. The use of video data enabled
researchers to examine the role that non-verbal language played in conversa-
tions. For example, Goodwin (1979) famously examined how the single
phrase, ‘I gave up smoking cigarettes one week ago today actually,’ was aug-
mented 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 convers-
ing 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. How-
ever, 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 indi-
vidual 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 spec-
ification 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 SFL) has.

In summary, as Nevile (2015) describes, the 2000s saw an ‘embodied turn’ in LSI research: both by linguists through their increasingly multimodal efforts in SFL and social semiotics, and also by sociologists/anthropologists through their increasingly multimodal efforts in conversation analysis. Within linguistics and sociology/anthropology alike, researchers 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 communication 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 discussion of these cognitive approaches (which feature within Theme 2 of this thesis; see Section 6.1). In what follows here, I review the existing PER work that relates to LSI research in order to better relate my methodological approach to those who have attended to related matters in the context of physics education.

Across the first four papers of this thesis, I take the general approach of analyzing participants’ *multimodal* interaction on a moment-to-moment basis. To do so, I make use of a conversation-analysis-style methodology more resembling the work of scholars such as Goodwin and others. However, especially in Paper III, I incorporate the perspective of multimodal social semiotics due to the way in which it allows me to compare participants’ utterances with the socially-organized discipline of physics. As such, I see my research in Paper III especially, but also the entirety of the work in my thesis, as an embracing the ‘embodied turn’ which has occurred in LSI within the past two decades. Russ and Odden (2018) state that 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.

**Existing PER work related to my general methodological approach**

A number of physics education researchers have examined topics that readily relate to my methodological approach inspired by multimodal conversation
analysis. In their review of PER, Docktor and Mestre identify a subset of research on focused on language use. The work they review has investigated, for example, how the seemingly subtle changes in the words used to refer to a concept can affect students’ conceptual understanding (e.g., heating vs. heat in Brookes & Etkina, 2015; radiating vs. radiation in A. Johnson, 2020). Other PER literature related to language use includes research on how students make use of multiple representations (e.g., Van Heuvelen, 1991b; Van Heuvelen & Zou, 2001). Still other researchers have focused on the role of analogies in structuring student reasoning (e.g., Clement, 1993; Duit, 1991; Haglund & Jeppsson, 2012; Niebert et al., 2012)—often framed by the conceptual metaphor work by Lakoff and Johnson (1980), which I mentioned above and will examine in more depth with Paper III (Section 6.1). Some researchers have utilized Halliday’s SFL to study the functional grammar of physics learning (Brookes & Etkina, 2007, 2009, 2015). A common feature of most of this language-related work in PER is the examination of physics students’ reasoning via their written or spoken language. Thus, 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 the social semiotics work of Uppsala University PER Group, detailed below, as well as Gregorcie, Planinsic, et al., 2017; Harrer, 2018; Scherr, 2008; Scherr et al., 2013; Scherr, Close, Close, et al., 2012; Scherr, Close, McKagan, et al., 2012; Stephens & Clement, 2010).

Parallel to the work done in representations and language, a number of physics education researchers at Uppsala University and elsewhere have recently incorporated social semiotics into their examination of physics teaching and learning (e.g., Airey & Linder, 2017; M. Eriksson, 2020; M. Eriksson et al., accepted; M. Eriksson et al., 2019; Fredlund, 2015; Fredlund et al., 2012; Fredlund, Linder, et al., 2015a; Samuelsson et al., 2019; Volkwyn et al., 2019, 2018, Weliweriya et al., 2019, 2018). Social semiotics can be thought of as 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 start from the meaning potential of semiotic resources used in the discipline of physics. As Airey and Linder (2017) discuss, the 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 approach 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. 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 participants 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 the language-related work of PER: that is, in relation to the application of social semiotics to physics teaching and learning. In addition to the conversation-analysis-inspired approach I take across the first four of my papers in collecting and analyzing participants’ interactions, in Paper III 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 pair of participants in my data for Paper III. 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, again see Section 6.1.

4.3.2 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, for example, Hammer & Berland, 2014), 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. 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. 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—more precisely, what I have interpreted a multimodal transcription as entailing in this thesis, since the practice of multimodal transcription has little consensus on any one approach (Jewitt,

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27 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.
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), work/energy (Tang et al., 2011), and forces (Stephens & Clement, 2010).

My use of illustrations
In this thesis, I make particular use of line illustrations for my multimodal transcription of data and in this section, I examine their use in multimodal transcripts. I begin by highlighting some key considerations regarding the use of line illustrations for my presentation of qualitative data in academic publications. 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.

Advantages of illustrations versus pictures/frames of video
For my research, 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 video data is collected in authentic teaching environments (or even close approximations to these environments, as with my data) with common, non-‘professional’ 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 a particular 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, in my use of illustrations I am able to further highlight specific details and features of a given interaction.

Furthermore, my use of illustrations allows me to go beyond a simple recreation of a picture or frame of video in highlighting elements of participants’ interactions. For example, in Figure 6 (next page), which is an illustration used in Paper II (see Section 5.2.4), I have inset a magnified view of a menu alongside the outline of three participants in a learning environment to provide a clearer rendition of the participant’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 6. The fine control in creating these types of visual techniques is uniquely afforded to illustration. In a way, illustrations like Figure 6 might be interpreted as semi-schematic diagrams for qualitative data, whereby I 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 (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 illustrations, on the other hand, I 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. Asplund and Kilbrink (2020) employ a technique whereby they present stills from their video that only have the participants’ faces ‘drawn over.’ Such an approach, which blends illustration with pictures, may be advantageous for those researchers who want to represent the full detail of the background in their data while preserving some of the facial details that are relevant for their analysis/discussions, but who also want to maintain their participants’ anonymity. For a further discussion of anonymization and ethical treatment of data, see Section 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 partic-
ular 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. I have been able to simply alter the erroneous segment of the outline in isolation. Especially as I have generated various iterations of an illustration, which should almost certainly be done if a high-quality illustration is desired, the vector-based approach has given me 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 of 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 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 doctoral thesis.

4.4.1 Trustworthiness

First, I argue for the trustworthiness of my doctoral 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 camps (see, for example, Wolcott, 1994). However, in this thesis, I side with Robson and McCartan (2016), Robertson et al. (2018), Guba and Lincoln (1982), and Bassey (2001) in the stance that ‘traditional’ questions of rigor and quality 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 methodological camp, 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, respectively\(^28\) (see Table 5, next page). In order to accommodate the differences in axiomatic assumptions that case-oriented research (in their words, “naturalistic inquiry”)\(^29\) 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).

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.

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\(^{28}\) 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).

\(^{29}\) 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.
### Table 5. 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].

<table>
<thead>
<tr>
<th>Trustworthiness questions</th>
<th>Recurrence-oriented answers</th>
<th>Case-oriented answers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Truth value</strong></td>
<td>Validity</td>
<td>Interpretative validity [credibility]</td>
</tr>
<tr>
<td><strong>Applicability</strong></td>
<td>Generalizability</td>
<td>(Fuzzy) Generalizability [transferability]</td>
</tr>
<tr>
<td>(Scientific and probabilistic)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Consistency</strong></td>
<td>Reliability</td>
<td>Reliability [dependability]</td>
</tr>
<tr>
<td><strong>Neutrality</strong></td>
<td>Validity</td>
<td>Interpretative validity [confirmability]</td>
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### 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 6500 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 doctoral 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 participants 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 reports—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 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. Furthermore, by flagging that translation of data has occurred in my work, including transcripts where possible in the original language (see Appendix G), reporting on who has done the transla-

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30 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.

31 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.
tion, and double-checking our translations, I have strived in this thesis to follow recommended guidelines for reporting research data in another language than the one in which it was collected (Taber, 2018). 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 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. 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). My goal has been to use my theoretical perspectives (discussed in Chapters 5, 6, and 7) in a sound way so as to give rise to analyses that represent my understanding of participant interactions when seen against the 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 doctoral 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 dataset was originally collected with the purposes of comparing *Algodoo* 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. 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 participants’ interaction.

**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:

[...]

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.

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 et al., 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 scientific research.

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)\(^\text{32}\)—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 research has satisfied these conditions for not requiring an external review by an ethical board in that I have not collected personally sensitive data and insofar as the data collection I conducted did not pose a threat of physical or psychological harm to any of my participants. 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 video data, my research has involved the handling of ‘personal data.’ Accordingly, 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 a secure manner.

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 (even taking additional steps to be ethically compliant in my collection of data outside of Sweden, see the section

\(^{32}\) Accessible with the following link: www.riksdagen.se/sv/dokument-lagar/dokument/svensk-författningssamling/lag-2003460-ometikprovning-av-forskning-som_sfs-2003-460.
on Collaborative Institutional Training Initiative Certification below). 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) a pre-participation consent form, and (3) an extended consent form to be completed following participations. Blank copies of each of the ethical forms discussed in this section are included in the appendices. Appendix B includes the consent forms used in collecting the first dataset. In Appendix C and D, I include the consent forms utilized by Gregorcic (in Slovenian) and Rådahl (in Swedish) for the collection of the second and third datasets, respectively. In Appendix E, I include the consent forms used in conjunction with the fourth dataset.

In the first of these forms (Appendix B), 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 participants 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 by 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 4.3.2, I ended up utilizing line illustrations for the presentation of my data and this allowed me to avoid the blurring of participants’ faces while maintaining a degree of anonymity.

Anonymization
For the purposes of anonymizing the data collected for this thesis, I have assigned each participant with a pseudonym or code (e.g., ‘P1’ for Participant 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 University\textsuperscript{33}—decide 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).

**Collaborative Institutional Training Initiative Certification**

For the purposes of collecting the fourth dataset at the University of Colorado (CU Boulder) Boulder, I was required to get certified to do ‘Social Behavioral Research’ on human subjects provided by the Collaborative Institutional Training Initiative (Record ID: 24517233). This was done in compliance with CU Boulder’s ethical rules and regulations for education research, which are more broadly enforced as part of the ethical policies in the U.S. for human subject research.

\textsuperscript{33} 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.
The Three Themes of this Thesis
5 Theme 1: Bridging the physical and formal

I have so far used the preceding chapters in this thesis to discuss the context of existing work on digital technologies in PER, a taxonomy of DLEs as meaningfully situated in broader learning environments, and my general methodological position of case-oriented research. Now in this fifth chapter, I present the first research theme of three that comprise the results of my doctoral work. Theme 1 (from Papers I and II) deals with the potential for less-constrained DLEs like Algodoo to bridge the gap between the physical intuitions of students and the formal mathematical resources endemic to disciplinary physics. In exploring this theme, I have examined the relationships between students, a DLE, and the physical world (Figure 7).

![Diagram](image)

Figure 7. The emphasis of Theme 1 on the interactions between students, the physical world, and a DLE; depicted within the broader ecosystem explored by this thesis.

The research question at the core of Theme 1 (RQ 1) is,

As a concrete example of a less-constrained digital learning environment, how can Algodoo be observed to act as a mediator for students between the ‘physical world’ and the ‘formal world’ of physics?
I answer this question through the interpretivist analyses of three case studies. My doctoral research began with Paper I, wherein I first explored how participants made use of Algodoo on an IWB in small groups. Thereafter in Paper II, I analyzed the structure of this less-constrained DLE in greater theoretical depth. Here in Chapter 5, I discuss the two papers together under Theme 1. The structure of this chapter presents the two papers in parallel fashion (in Sections 5.1 and 5.2 respectively). For each of the two papers, I first discuss the perspectives I included in my analyses of the cases (Sections 5.1.1 and 5.2.1), I review how I selected the specific data for the case studies (Sections 5.1.2 and 5.2.2), I detail the approach I took in transcribing the data (for analysis and presentation in manuscripts, Sections 5.1.3 and 5.2.3), and finally I present my findings (Sections 5.1.4 and 5.2.4). In the final part of this chapter, I discuss the work of Papers I and II together, ultimately forming a picture of how DLEs can mediate between the physical and formal ‘worlds’ of the subject of physics (Section 5.3).

5.1 Semi-formality and modeling with DLEs (Paper I)

As discussed in Chapter 4, Paper I involved the first dataset, wherein I studied how a pair of participants used Algodoo on an IWB alongside a physical laboratory setup. Even from this first paper of my thesis work, I was interested in exploring how Algodoo might be observed to make the mathematical formalisms of physics more readily relatable to the intuitions of students. This was prompted after I stumbled upon the notion of DLEs functioning as semi-formalisms during my readings of diSessa (1988). In fact, I had been reading diSessa’s publication in order to familiarize myself with the notion of ‘p-prims’ (taken up in more detail within my discussion of the perspectives taken in Paper III, Section 6.1.1), but I was surprised to see that the second half of diSessa’s discussion centered on how DLEs could be particularly outfitted to leverage students’ intuitions while engaging those students in mathematically-rich problem solving; this was at the core of diSessa’s notion of a semi-formalism. However, with a cursory search of the literature, I found that essentially no work had been done to examine students’ use of DLEs using this theoretical construct. Thus, in Paper I, I was motivated to explore how students’ multimodal interactions could be used to reveal the degree to which a software like Algodoo was functioning as a semi-formalism. To do so, I combined the idea of semi-formalisms with Hestenes’ (1992) notion of Newtonian modeling games. This allowed me to structure my analysis of participants’ interaction around three domains: the physical world (the physical ramp setup), the semi-formal world (the DLE, Algodoo), and the formal world (the mathematical representations included in Algodoo). For the purposes of this analysis, I treat the graphs within Algodoo 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 the perspectives involved in Paper I in more detail.

5.1.1 The perspectives taken in Paper I

In Paper I, I employ and combine diSessa’s (1988) notion of semi-formalisms with Hestenes’ (1992) modeling perspective. In what follows, I further discuss both of these perspectives and how I bring them together in the analysis of Paper I.

DLEs as semi-formalisms

Computers have a very special niche at the interface between, on the one side, formalisms—those grand unifiers of science where one can write down “F=ma” and summarize all of Newtonian Mechanics in a little box—and, on the other side, experience with its apparently infinite fragmentation. (diSessa, 1988, p. 63)

The first of the perspectives used in Theme 1 is the notion of DLEs acting as semi-formalisms. In the early years of research into computer-supported learning in physics, diSessa (1988) described a unique role for computers in crafting interactive environments. He hypothesized how computers might act as semi-formalisms, which he described as digital access points to the formal ideas of physics that could be strongly related to students’ intuition. In this thesis, I make use of diSessa’s term, semi-formalism, to discuss how DLEs (like Algodoo) can play a mediating role between the physical world and the mathematical formalisms used in physics. I brought up the notion of semi-formality in my discussion of DLEs in Chapter 3 (as relevant for the discussion on relating less-constrained DLEs like Algodoo to programming DLEs) and this is a point I return to in Chapter 8. For the purposes of my analysis in Theme 1 here, it is important to note that my use of this perspective combines diSessa’s semi-formalisms with another theory that discusses the relationship between the physical and formal worlds of physics: Hestenes’ (1992) modeling perspective.

Modeling

The second perspective that I make use of for Theme 1 is the notion of modeling as described by Hestenes (1992). 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 as a scientific activity. For him, this means that physics teachers should create learning environments that reveal to students how modeling underpins the constitution of physics knowledge. In this way, Hestenes and others endorse
the philosophy that enabling students to build, inspect, and use models is at the core of quality physics teaching (Hestenes, 1987, 1995; Jackson et al., 2005; Wells et al., 1995).

For the purposes of Theme 1, I have combined the theoretical ideas of diSessa and Hestenes for the examination of students’ use of the less-constrained DLE Algodoo. Figure 7 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 bodily experiences of the physical world). In Figure 7, I depict a DLE semi-formalism as a vertical halfway point between Hestenes’ (1992) two worlds.

Figure 7. 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 (reproduced from Paper I under the CC BY 3.0 license).

5.1.2 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
participants from the second session of the three 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.

5.1.3 Transcription

To analyze the participants’ actions during the session, I generated a multimodal transcription (see Section 4.3.2) of the video in which I explicitly notated the participants’ 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. In a table, three columns were devoted to each participant (one for logging the participants’ talk, one for logging gestures, and one for logging interactions with the environment) and two columns were devoted to logging the interactions 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 participants’ interaction in this manner helped me interpret the most meaningful, short exchanges pertinent to semi-formalisms and modeling. In the following section, I have highlighted three specific exchanges. The two participants are labelled Participant 1 (P1) and Participant 2 (P2), while the researcher in the room conversing with them in the lines shown below is labelled Re. The ‘full’ transcript generated from this dataset can be found in Appendix F.

5.1.4 What I found (analysis and discussion)

For the analysis in Paper I, I tracked how the participants came to understand the ramp-puck situation (Figure 5, p. 66) by moving between three domains within the activity: namely, the physical ramp, the two-dimensional scene within Algodo (where the participants 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 participants created and interpreted the two-dimensional model they created in Algodo from a multimodal perspective to track how each of these three domains was involved in their process of meaning making. Before reviewing three instances of participants moving between these domains, I
briefly review the general progression of the participants’ activity during the session for context.

The participants 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 Algodoo. Their digital model in Algodoo 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 Algodoo constitutes an automatically-generated infinite plane). The participants 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 Algodoo for a short time, the participants 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 participants 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 participants’ construction of the digital model to highlight instances where the participants 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 participants for making meaning (where ‘Ph’ represents the physical domain, ‘S-f’ represents the semi-formal domain, and ‘F’ represents the formal domain). In doing so, the figures included in this transcript make use of a minified version of the semi-formal modeling diagram from Section 5.1.1 (Figure 7, p. 97). In each of these examples, the participants were not explicitly directed by the researchers to incorporate multiple domains.

Figure 8 (next page) shows an exchange during the first steps of the digital model construction. The participants 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). Participant 2 then asked if there was a way to achieve this rotation in Algodoo. When one of the researchers asked where the participant desired the center of rotation to be, Participant 2 replied by pointing to the end of the physical ramp instead of the corner of the rectangle within Algodoo (line 3). This example
1. P1: Is there any way for this software to change the center of rotation?

2. Re: Where would you like the center of rotation to be then?

3. P2: Down here. [points to base of the ramp]

Figure 8. Participant 1 uses the bottom of the physical ramp to explain the position around which he wanted a rectangle in Algodoo to rotate (reproduced from Paper I under the CC BY 3.0 license).

4. P2: We have to look at it from here to there. [points to the graph]

5. P1: Hits the ground here. [points to the inflection point in the graph where the line intersects the x-axis]

6. P2: Yeah we want to know the distance... here? [gestures to show a horizontal distance at the table]

Figure 9. Participant 2 uses an environmentally-coupled gesture next to the ramp to clarify a distance while trying to interpret a plot in Algodoo (reproduced from Paper I under the CC BY 3.0 license).

7. Re: And where would you like [the zero] to be?

8. P1: Here. [points to the top of the tilted rectangle]

9. P2: No... we want it on the end there. [points to the right edge of the horizontal rectangle]

Figure 10. Both Participant 1 and 2 point to locations within the Algodoo scene to demonstrate where they wanted to align the y-axis (x = 0) in a graph they had generated (reproduced from Paper I under the CC BY 3.0 license).
showcases a participant using the physical domain to elaborate a point within the semi-formal domain—i.e., movement between the physical domain (Ph) and the semi-formal domain (S-f).

Figure 9 (previous page) shows an exchange after the participants had created the digital model and were trying to track the horizontal distance that the circle travelled before hitting the ground within Algodoo. To do this, the participants generated a plot of the y-position vs. the x-position of the circle. However, as the participants 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, Participant 2 proceeded to gesture next to the physical table while he posed a question to the researchers (line 6). This exchange showcases an example of a participant using the physical domain to make meaning in the formal domain of the graph—showcasing movement between the physical domain (Ph) and the formal domain (F) (note again that, in these examples, both the formal domain and the semi-formal domain are accessed through Algodoo; 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 (previous page) shows an exchange shortly after the exchange in Figure 9 where the participants were deciding where to place the y-axis of their graph within the Algodoo scene so that they could read off the horizontal distance from the x-value directly. As the participants 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 participants 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 (lines 8 and 9). This exchange showcases an example of the participants using the semi-formal domain to explain their reasoning about an aspect of the formal domain—i.e., movement between the semi-formal domain (S-f) and the formal domain (F).

In each of the examples shown above, the participants clarified their reasoning by moving between domains. That is, when faced with a question about their digital model in Algodoo, for example, the participants answered by pointing to a distance in the physical ramp setup. By tracking the moment-to-moment meaning-making of the participants in the form of talk and environmentally coupled gestures, the instances where the participants were articulating their reasoning across domains are made visible. This type of attention could be paid to with 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 DLEs like Algodoo. In this way, the degree to which a particular tool (digital or otherwise) acts as a semi-formalism for certain students could be ana-
lyzed. Such a focus could provide the interested researcher with a unique in-
sight into the roles that physics tools play in physics learning. For example, I
might propose the following hypothesis to be tested in the future:

\[\text{The inclusion of less-constrained digital learning environments (like Algodooh) in }\]
\[\text{physics activities increases the likelihood that students will draw conceptual par-}\]
\[\text{allels between the physical world and the formalisms used in physics.}\]

This hypothesis, whose exploration would surely aid in understanding the de-
gree to which DLEs can be leveraged as semi-formalisms, could for example
be tested in a comparison study between students given Algodooh, students
given a constrained DLE (such as a PhET simulation), and students given no
DLE whatsoever. In the progression of this thesis, the work done in Paper I
can be seen as my first foray into studying students use of Algodooh on an IWB.
The techniques and insights gained from this short study were lessons I
adapted for a further exploration of the mediating role of Algodooh in Paper II.

5.2 Microworldiness (Paper II)

After beginning to explore how a DLE like Algodooh could function as a me-
diator between the physical and formal worlds in Paper I, I was motivated to
explore the theoretical underpinnings of semi-formality with DLEs. In rela-
tively short order, I found the foundational writing of Papert (1980a), the CC
scholar mentioned in Chapter 2 who first wrote about the potential for com-
puters to bring the formal systems of mathematics into experienceable do-
mains. Papert’s perspective was something called constructionism and he re-
ferred to constructionist DLEs as microworlds. While distinct in its emphasis,
diSessa’s notion of a semi-formalism used in Paper I was largely a re-articu-
lation of Papert’s visions for DLEs in physics learning.

Thus, in a continued exploration of how DLEs like Algodooh could be ob-
served to bridge the formal ideas of physics into physically intuitive arenas, I
set out in Paper II explore the extent to which Algodooh could be seen as acting
as a microworld through students’ multimodal interactions. As I discuss be-
low, the definition of microworld originally adopted for Paper II of this thesis
is a user-subjective one (Rieber, 1996). Ultimately, in the context of my full
thesis work it is important to note that I have largely moved away from dis-
cussing the degree to which Algodooh can be seen to function as a microworld
(see Section 8.4). Nonetheless, in Paper II I examined the extent to which the
‘microworldiness’ of Algodooh could be observed during participants’ use of
the software in small group work. As discussed in Section 4.2, Paper II makes
use of the first and second datasets. In fact, the same group of participants that
were used in Paper I were selected from the first dataset. This case was studied
in combination with the second dataset in order to reflect on how Algodooh’s
potential microworldiness might provide students with alternate, informal means for engaging with formal (mathematical) ideas. In the sections that follow, I review the perspective of constructionism, how and why the data were selected, how transcription was carried out, and finally the analyses of the two cases themselves.

5.2.1 The perspective taken in Paper II

As a continuation of the work done in Paper I, Paper II employs the perspective of Papertian constructionism (Papert, 1980a) and, thus, makes use of the related notion of DLEs as microworlds. Both of these terms were brought up in Section 2.4 during my discussion of Controllable Worlds, but here I explain more specifically how I use this perspective in my research.

Constructionism (and microworlds) II

The third perspective that I make use of within Theme I (after semi-formalism and modeling in Paper I) is constructionism and the related notion of microworlds. Both of these terms came up in my discussion of Controllable Worlds in Chapter 2, but since I make explicit use of them in Theme I as part of Paper II, it is worth providing more detail here.

In *Mindstorms*, Papert (1980a) presented a family of computer-based tasks (‘Logo systems’) that involved small programmable robots alongside computers running the Logo programming language. Papert argued that Logo systems could provide students with a sufficiently enticing learning 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. As explained in Section 2.2.2, he invented the notion of *microworlds* and it is apparent that his hope with microworlds was to make computer programming and even the systematized formalisms of Newtonian mechanics readily accessible to students. In contrast to what he considered the often ineffective and ingenuine approaches taken by much of traditional education, Papert believed that students’ use of microworlds would result in “Piagetian learning,” or informal “learning without being taught” (p. 7). Papert argued that this could be done by providing arenas which were rich in the building blocks needed for students to explore, create, and experience.

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34 Side note: the learning environment advocated for by Papert here is an interesting example of a construction kit facet distributed between a digital programming environment and a physical robot. In the distribution of facets between digital and non-digital (manipulable) artefacts, the learning environment advocated for by Papert resembles many of the learning environments that employ ‘probeware’ discussed in Section 2.3.
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.

Recall the context-dependency I assume with respect to DLEs, as discussed in Section 3.2: a DLE should be judged as a microworld in its specific use within a particular context. In Paper II, I examine the extent to which Algodoo can be seen to function as a microworld (i.e., I determine its functional microworldiness). Regardless of whether or not Algodoo can be unanimously identified as a ‘microworld’ for all students, I concern myself in Paper II with the extent to which Algodoo functions as a microworld for certain the participants in my data as they use it to deal with mathematical concepts in a physics context. To more clearly operationalize this, I examine the extent to which Algodoo can be observed to (1) offer the correct mathematical materials for students to recruit and (2) provide an adequately creative space within which students could be inspired to create with these materials.

Informal physics learning II

Before presenting the analyses of Paper II, it is useful to review how the notions of constructionism and microworlds relate to idea of informal physics learning. 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 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 that 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 common, 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.

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. 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 conceptual 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 classroom, an everyday experience with speedometers does not 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 Algodoo can provide experienceable situations to students which might act in a similar manner to the speedometer. That is, I am interested in how Algodoo might provide students with access to materials which they can recruit in the construction of their own understanding of physics. I suggest that especially when combined with the appropriate broader learning environment, Algodoo can not only afford students with experiences of mathematical ideas as they are used in physics but can also provide an arena for students wherein 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 Algodoo 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 dataset discussed in Section 4.2), I use both cases to reveal the manner in which the presence of representational options within Algodoo led the participants 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 dataset collection was to examine how participants used Algodoo in combination with a physical setup (Paper I). However, in both this first dataset and the second, I found short examples of participants engaging with a variety of mathematical representations in novel ways. I saw the participants coordinating their physical observations and mathematical ideas within Algodoo 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 participants and also their gestural activity, Paper II includes a multimodal transcript comprising written excerpts of talk\(^{35}\) and line illustrations drawn from frames of the video data (which are occasionally augmented by closeups of the relevant Algodoo menus). Each line of the transcript is numbered and labelled with the person responsible for the speech or action contained in the line (continuing from the lines of transcript from Paper I, labelled ‘P3’ to ‘P7’ for Participant 3 to Participant 7, respectively, and ‘Re’ for researchers). Expanding on the transcription style from Paper I, actions such as gestures or manipulations of the IWB are included as italicized text in [brackets] and represented visually by illustration when useful. Each excerpt of transcript is followed by a summary of what was said and done by the participants to make explicit the things I wish to highlight from the participants’ interactions.

5.2.4 What I found (analysis and discussion)

**Case 1: Vector-sense with the ‘Velocity’ tab II**

The first case examined in Paper II involves an excerpt from the second dataset, wherein a group of three participants 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 participants 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 three participants 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

\(^{35}\) 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.
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 participants observed the collision.

10 P4: Okay…
11 P3: Aha!
12 Re: What happened now?
13 P3: This one’s trajectory changed, but it remained constant.
14 P3: And it’s losing speed.
15 P4: No, it’s not losing speed.
16 P3: [points to the slider for speed] (Figure 11)
17 P3: One of them is losing speed.
18 P4: Yeah, yeah. That one.
19 P3: Yeah, that one, yeah. That one that is going away.
20 Re: Ah, now you’re looking at that one!

In this exchange, the participants 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 Participant 3

Figure 11. Participant 3 (left, with Participant 4, middle, and Participant 5, 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 14)36 (reproduced from Paper II with permission from Springer Nature).

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36 It should be noted that the values for Speed, Angle, etc. in the Velocity menu of Figures 11, 12, and 14 are an approximate recreation and do not necessarily reflect the exact values seen by the participants during the session (no screen capture was available to determine these values as they originally appeared). 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.
refers to as being “constant” (line 13)—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 participants 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 Algodoo.

[continued from above]

21 P5: Turn its angle, so it will come back.
22 P3: [laughs]
23 P4: [starts dragging the Angle slider to the right, changing the angle at which the runaway planet is travelling]
24 Re: You can also turn the little wheel if you want to turn the angle. There, on the right side.
25 P3: 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)
26 Re: So, you noticed something interesting.
27 P3: So, now it’s slowly coming back into orbit. Because it’s becoming faster. [points to the speed slider, where the value is increasing]
28 P5: Yes.
29 P4: Yes.

Figure 12. Participant 3 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 25). Participant 5 points toward the wheel of the velocity menu as it turns with the changing trajectory of the planet (reproduced from Paper II with permission from Springer Nature).

Here, Participant 5 suggested that they “turn [the planet’s] angle” (line 21) in order to bring it back into sight. Participant 4 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 4 could have also used the Wheel to change the angle. After Student 4 changed the angle, Student 3 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 27) and the other two participants agreed.

[continued from above]

30 Re: Coming into orbit, what does that mean?
31 P5: Closer…
32 P3: Closer to the [Sun].
33 P4: 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]
34 P3: Just a moment. Considering it was travelling away from this object and it was losing speed…
35 P4: Yes, it was.
36 P3: And there was no resistance…
37 P4: It was in orbit from the beginning, but…
38 Re: Okay. Okay. Interesting observation. It was flying away. It was losing speed.
39 P4: It was losing speed and it had no resistance. 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) Which is interesting- but, I mean, it’s interesting…
40 P3: Yeah, I get it.

Figure 13. Participant 4 is shown gesturing to show the movement of a planet as it is accelerated by the Sun (line 39). I interpret this explanation as one that uses a Newtonian model of Sun-planet interaction (reproduced from Paper II with permission from Springer Nature).
Here, the participants engaged in a discussion about orbital motion and the underlying mechanisms that govern the changes in an object’s velocity. Though Participant 3 initially had an issue with the planet slowing down in a frictionless environment, Participant 4 was able to explain how the object’s behavior made sense in a system with gravitational force (line 39). Participant 4 supported his reasoning with environmentally-coupled hand gestures, symbolizing the movement of the planet and the direction of forces (Figure 13).

(continued from above)

41  P3: Aha, okay, now its angle started changing, which means… [repositions himself in front of the IWB, pointing to the Velocity tab] (Figure 14)
42  Re: Oh, yes, now you are observing that body just through [the Velocity tab].
43  P4: Yeah, um… Good point.
44  P3: [laughs]
45  P4: [uses the Zoom tool to zoom out, revealing more of the space around the Sun]
46  P3: Here it is. [notices the runaway planet on the left side of the Sun, close to the edge of the screen]
47  P4: It’s here. [pointing to the runaway planet]
48  P3: Let’s do it by hand.
49  P4: Let’s zoom out more. Can we zoom out more?
50  P3: No.
51  Re: This is the most zoomed out it can be.
52  P3: Quickly. [turns the angle wheel CW, in the direction toward the Sun]
53  P4: But now we are changing its things again.
54  P3: [drags the speed slider to the right and the planet starts traveling faster toward the Sun]
55  P4: It is going to crash directly into it.
56  P3: [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. Participant 3 notices the changing velocity of the runaway object in the Velocity tab. He positions himself in front of the IWB and points to the changing Angle slider (line 41) (reproduced from Paper II with permission from Springer Nature).
Again, Participant 3 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 participants were interpreting the motion of the planet through looking at the values in Velocity tab, to which the participants 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. Participant 3 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, Participant 3 watched the object and the Velocity tab simultaneously and noticed that the Speed slider continued to move to the right as the object accelerated toward the Sun (Figure 14).

In the excerpts of transcript presented above, it can be seen that, although the participants 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 participants 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 participants were then able to propose explanations (which I identify as consistent with a formal, Newtonian model)\(^{37}\) 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 participants 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 participants 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 participants 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 participants then used the Velocity tab to manipulate the

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\(^{37}\) This type of interpretation here of the participants’ reasoning, especially in how it ‘resembled’ a formal idea used by the physics discipline, is something I explore further in Paper III.
object’s motion dynamically (with Algodoop running). This manipulation appeared in two instances within the data above: first, as Participant 3 changed the angle of the object’s velocity (line 23) and again when the same participant redirected the object toward the Sun (lines 52-56). In both of these instances, the presence of Algodoop’s Velocity tab, which allowed Participant 3 to set and manipulate the velocity of the object with sliders and a wheel, provided an opportunity for the participants to engage with the orbital task creatively. More 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 participants 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 Algodoop’s microworldiness: the software seems to have provided the participants with mathematically-rich materials, while also allowing the participants 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 Algodoop 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 Algodoop environment, the participants 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 participants were able to demonstrate some degree of fluency in vector-sense for two-dimensional motion. The presence of the Velocity tab allowed the participants 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 Algodoop—which made the participants 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 participants 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 participants, 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 participants noticed one of the objects “losing speed” (line 14), after which Participant 3 started making sense of the changing angle and slowly-increasing velocity of the runaway planet with an explanatory gesture (line 25). Participant 3 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\textsuperscript{38}). He then 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 Algodoo-IWB learning environment was successful in encouraging participants to spontaneously produce an explanatory model for the patterns of motion. This can be seen when Participant 3 questioned the motion of the runaway object (line 34). Participant 4 responded by proposing an explanation for the patterns of motion consistent with a Newtonian model of orbital motion (line 39). Participant 4’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 Algodoo appears to have behaved as a point of departure for further inquiry, providing some mathematical materials which participants 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 Algodoo can potentially act as a microworld for physics students. That is, the participants in this case 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 Algodoo 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 of used by scientists, all while promoting active engagement and creativity.

I have shown here with Case 1 that, when using Algodoo, students can use mathematical representations in a creative way, therein becoming inspired to discover how a physical system works. The participants’ use of the mathematical materials provided by Algodoo was both playful—due to Algodoo’s less-constrained design—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 Algodoo is an explorable ‘sandbox’

\textsuperscript{38} Transduction can be thought of as the process of re-expressing the meaning from one semiotic system to another (e.g., describing a picture in words or gesturing the motion of 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). Nevertheless, while the case studies in my doctoral thesis could readily adopt a transduction analytic focus, I do not take up the topic for the sake of brevity.
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 Algodoo that resulted in the participants 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 (see Chapter 7 for more on the role of the teacher alongside less-constrained DLEs). Throughout the activity, the researcher engaged with the participants to help direct them in their exploration. If the participants had simply been given the Kepler’s law scene without any instruction or guiding activity, it is possible that they would not have ended up manipulating the velocity in such fruitful ways. Nonetheless, for the purposes of this analysis, it is worthwhile to recognize that the participants’ creative behavior and inventive use of formal building blocks showcases the apparent microworldiness of Algodoo in this particular context.

**Case 2: Kinematics with ‘Show Plot’ II**

I now present the second case from Paper II to illustrate the potential for Algodoo to promote creative and meaningful use of mathematical representations. This case, which was selected from the first dataset, focuses again on the pair of participants from Paper I that used Algodoo alongside a physical ramp and a hockey puck on a table (see Section 4.2.1). The particular excerpt of transcribed data that I present here shows how one pair of participants, now (for the sake of clarity in distinguishing between my different analyses) referred to as Participant 6 (P6) and Participant 7 (P7), 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 participants were able to recruit and interpret graphical representations in Algodoo as they attempted to quantify a physics phenomenon.

My presentation of the data starts as Participants 6 and 7 finished setting up a virtual model of the ramp-puck experiment in Algodoo. They place two rectangular objects (representing the ramp and the table) and the circular object (the puck) in such a spatial arrangement (Figure 15, next page) that when they press the play button, the puck rolled down the ramp, continued off the table, and then hit the ground below. The participants 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.

After constructing the virtual ramp-puck setup, the participants ran the scene to check the function of their model. The circle successfully rolled down and off the rectangles before hitting the ground. The participants had an immediate desire to measure the distance that the puck travelled from the edge
of the horizontal rectangle, but *Algodoo* does not include a purpose-built distance measuring tool. Participant 6 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 *Algodoo* allows you to choose to plot different quantities on the horizontal and vertical axis of the displayed coordinate system.

57 P6: [sets the vertical axis to ‘Position (y) and then the horizontal axis to Position (x)]

58 P7: [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]

59 P7: Something like that.

60 P6: And start?

61 P7: Yeah.

In the first part of the excerpt, the participants 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 *Algodoo*, the participants discovered the ‘Show Plot’ tool. Participant 6 then interacted with the plotting tool to select

*Figure 15. Participant 7 (right) 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 as a virtual ramp, and the circle 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 at the bottom of the screen and gravity acted vertically downward (reproduced from Paper II with permission from Springer Nature).*
the appropriate axes labels (the x-position and y-position of the virtual puck) and Participant 7 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]

62  **P6:** [presses the play button and watches the puck move with the data being drawn in the graph window simultaneously] (Figure 16)  
63  **P7:** And let’s see. If we look closer at this… [leans in to examine the graph]  
64  **P6:** Here. [points to the point on the graph corresponding to where he thinks the circle hit the ground]  
65  **P7:** Yeah there. [pointing to the same point as P6] 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]  
66  **P6:** Hits the ground there. That’s what we need to get.  
67  **P7:** 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]  
68  **Re:** Mhm.  
69  **P7:** Yeah. Uh… [pauses for a long time to examine the graph]

Figure 16. The participants are shown examining the scene after watching the circle roll down the ramp and off the table (line 62). The graph displays a plot of the circle’s motion (reproduced from Paper II with permission from Springer Nature).

In the second part of the episode, the participants 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 Algodoo 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

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39 This line and the next two were originally studied in Paper I (Section 5.1.4).
setup and then pointed out what they interpreted as the corresponding distance on the graph.

[continued from above]

70  P7: 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?

71  Re: Mhm. Is there a question?

72  P7: 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]

73  Re: So, what is this graph displaying really?

74  P7: The y-position [gestures up and down the IWB] and the x-position. [gestures left and right along the IWB] (Figure 17)

Figure 17. Participant 7 gestures to describe what each of the axes is displaying (line 74). He explains 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) (reproduced from Paper II with permission from Springer Nature).

75  Re: Mhm.

76  P7: 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]

77  Re: 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.

78  P7: Yeah it describes exactly where the ball has been. It shows the path of the ball.

79  Re: Mhm! So, in space, right?

80  P7: In space, yes.
Re: So, I think you can actually see where the x-zero is then.

P7: 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)

Figure 18. Participant 7 points 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 (line 82) (reproduced from Paper II with permission from Springer Nature).

Re: And where would you like it to be?

P6: Here. [points to the upper corner of the tilted rectangle] (Figure 19, left)

P7: 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. Participant 6 is shown pointing to the position he thinks is best for the $x = 0$ position at the top of the tilted rectangle (line 84, left image). Participant 7 disagrees and points to the end of the horizontal rectangle (line 85, right image) (reproduced from Paper II with permission from Springer Nature).
In this exchange, the participants 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. Participant 6 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 85, with some technical help from the researchers, the participants repositioned the objects in \textit{Algodoo} so that the right edge of the horizontal rectangle (the virtual table) was positioned at \(x = 0\). This was required since \textit{Algodoo} 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]

86 P6: [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 reposition as they wanted]

87 P7: [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)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig20.png}
\caption{Participant 7 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 (line 87). He is then able to read off the value for the horizontal distance from the \(x\) coordinate of the dynamic graph label (reproduced from Paper II with permission from Springer Nature).}
\end{figure}

In this last excerpt from Case 2, the participants 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 transcript from Case 2, I present how the participants stumbled upon the ‘Show Plot’ tool in Algodoo 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 participants first had to interpret what the graph was showing so that they could understand how Algodoo had placed the origin for them (the origin is fixed by default to the background in Algodoo 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 participants engaged with the Algodoo-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 participants’ interaction in Case 2 to highlight how Algodoo appeared to act as a microworld by providing the participants with mathematical material to draw upon in a meaningful, if slightly unconventional, exploration of a physics phenomenon.

With the ‘Show Plot’ tool in Algodoo, the two participants 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 Algodoo 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 participants 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 participants measured a quantity with the graph rather than populating the graph with data measured by another tool. This is made possible in Controllable Worlds like Algodoo due to the fact that these software 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 participants 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 participants’ 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 participants 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 participants, they were still required to engage with the representation enough to responsibly select an appropriate version of the graph for their given situation. The participants 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 participants to use mathe-
matical representations in a creative, yet meaningful manner: the software provided the participants 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 participants is in how it conditioned their actual construction of a model of the ramp-puck setup. While the preceding transcript focuses on the participants’ use of the Show Plot tool, the participants’ mathematization within Algodoo began even before the excerpts of line 57, when they geometrized the ramp-puck setup into the virtual space. The participants 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 participants 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 participants 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, Participant 6 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 participants 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 participants 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 participants 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 participants 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 participant activity in Case 2 around the given prompt showcases how users of Algodoo can make creative, yet meaningful use of the representations within the less-constrained digital environment. The participants 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 Algodoo-IWB setup, they were able to determine the desired distance and continue with their task. This suggests that such Algodoo-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 Semi-formality: the mediating role of Algodoo between the physical and formal

In Papers I and II, I explore the extent to which DLEs like Algodoo can mediate between the physical and formal ‘worlds’ involved in the subject of physics. In doing so, I have sought to answer the question,

As a concrete example of a less-constrained digital learning environment, how can Algodoo be observed to act as a mediator for students between the ‘physical world’ and the ‘formal world’ of physics?

The terminology and framing adopted for both papers is slightly different, so in addition to summarizing how I have answered the above question for Theme I here, I will use this final section of Chapter 5 to combine the details of the perspectives from these two papers into the useful notion of a DLE’s semi-formality.

The analysis of Paper I (Section 5.1.4) shows how it is possible to observe students as they 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 participants in Paper I utilized a physical ramp, a construction-centered virtual space, and formal representations of motion (the latter two of which were accessed through the DLE, Algodoo). The participants 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.

Despite the domains having different dimensionality (Algodoo is a two-dimensional DLE, while the physical ramp takes up a three-dimensional volume), the participants frequently moved between the three domains with ease as they constructed and utilized their digital model of the physical ramp. It should be pointed out that during the data collection session of Paper I, I did not include any explicit discussion of the rules of the modeling ‘game’ that the participants played—a point that runs contrary to Hestenes’ (1992) recommendations. Nonetheless, later on in this thesis I examine further how DLEs such as Algodoo could be useful tools for teachers to discuss modeling in the explicit manner that Hestenes suggests (see also Gobert et al., 2011), and even,
perhaps, for discussing the epistemological issues surrounding the use of computer-generated models in the practice of science (Greca et al., 2014).

In the analysis of Paper II (Section 5.2.4), I examined how the structure of a DLE like Algodoo observably connects participants to the formalisms of physics by making them more physically intuitive. My analysis indicates that, for DLEs that are rich in the mathematical materials with which users can build and have experiences, it is possible for teachers to help students make conceptual links and to help them relate those conceptual links to mathematical formalisms. The cases presented in Section 5.2 show how the less-constrained structure of Algodoo inspired participants to informally create and explore with formal mathematical representations.

Thus, I recognize less-constrained DLEs like Algodoo as potentially valuable tools 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 intuitive understandings of physics phenomena. Especially when paired with an IWB, students using Algodoo may be able to experience physics phenomena through mathematical representations in much the same ‘physical’ ways that they can experience velocity and acceleration in our speedometer-rich culture. By bringing mathematical representations ‘to life’ within the dynamic system of a virtual world, DLEs like Algodoo might better convey representations as part of—and intrinsically related to—the phenomena of the physical world, 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 within a physical experiment.

So, now to combine some of the framings from the two papers in Theme 1. Both papers deal with how DLEs like Algodoo can provide access to the formalisms of physics through connections to the ‘real world.’ With Paper I, the participants are seen to relate formalisms within the DLE to a physical ramp setup through a process of semi-formal modelling. In Paper II, the participants are seen to make physically intuitive use of formalisms provided within the DLE. In both instances, the participants are seen to ‘get access’ to the formalisms of physics through a DLE-facilitated connection to the physicality of the physical world. In this way, Algodoo can be seen as bridging between the formal world of physics and the physical world of intuitions and sensory manipulation. In Paper II, I make use of the construct of ‘microworldiness’ to discuss the degree which a DLE (1) offers the correct mathematical materials for students to recruit and (2) provides an adequately creative space within which students could be inspired to create with these materials. This description of ‘microworldiness’ operationalizes the notion that DLEs can provide students with intuitive means of access (consistent with the ways of interacting with the physical world) to the formal norms and practices of disciplinary physics.
Nonetheless, as I have made clear several times in this thesis, the term ‘microworld’ comes with a considerable amount of baggage in the education research community. Thus, I suggest to fold this operational definition into the notion of a semi-formalism from Paper I. In the remainder of this thesis, I will use the term *semi-formality* to refer to the degree to which a DLE functionally mediates between the physical and formal domains of physics by providing a physically-intuitive *space* within which students can create with the formal *materials* of the discipline of physics. Similar to my framing of less-constrained and constrained DLEs (Chapter 3), the notion of *semi-formality* is especially germane to my discussion of how different *construction-kit*-functioning DLEs compare with one another. As I will explore more in Chapter 8, it seems reasonable to propose *semi-formality* as the continuum along which one can differentiate between the *construction kit* DLEs of ‘microworlds’ and programming.

Taken together, the analyses presented in this chapter show how less-constrained DLEs, especially those with a relatively high degree of semi-formality, can provide students with non-threatening opportunities to approach problems in uniquely self-directed ways. The *Algodoo*-IWB setup studied in Paper I and II fostered exploratory behaviour for relative newcomers to the DLE. This suggests that *Algodoo* and similar less-constrained DLEs could have potential for engaging learners in the early stages of mathematization through novel and less threatening ways than traditional instruction or classroom practices. While much of Seymour Papert’s constructionism work—and the well-known work of his colleague, Jean Piaget—focused on learning in young children, I argue from the findings of Papers I and II that *Algodoo* and other less-constrained DLEs have 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 learners with alternative, semi-formal means for accessing physics, but also allows learners to further develop, assess, and/or verify their understanding of the interplay of more complex physics and mathematics concepts with which they may already have experience (see also how responsive teaching approaches may be used to help facilitate such process in Chapter 7). In this way, I suggest that less-constrained DLEs have the potential to be useful for physics learners from elementary school through university. By giving students control to create with and choose from the many available mathematical representations within DLEs like *Algodoo*—as opposed to insisting that they use the ‘most appropriate’ representation for the task—the resulting activity can be student-directed and playful in nature, while at the same time meaningful from the perspective of conceptual learning. This is a notion that I carry into *Theme 2*, where I explore how students can use other non-disciplinary terminology and embodied meaning-making in the presence of DLEs to mechanistically reason about physics phenomena.
6 Theme 2: Embodiment and the making of meaning

In the previous chapter on Theme 1 of my thesis work, I dealt with the potential for DLEs like Algodoo to mediate between the physical, experiential domain and the formal domain that the discipline of physics so frequently asks students to move amongst fluidly (Volkwyn et al., 2020). In this way, Theme 1 represents the portion of my thesis where I explore the relationship that students might make directly with a DLE. Here in Chapter 6, I move onto the second theme of my thesis. Theme 2 (from Paper III) employs the perspectives of social semiotics, embodied cognition, and kinesthetic/embodied learning activities in order to examine with how physics students can engage in embodied interactions alongside DLEs while making meanings that are continuous with disciplinary physics. To reiterate, in this thesis I take ‘continuous’ with disciplinary physics (in terms of disciplinary-relevant aspects) to connote that the meaning-making resources made use of by students are consistent with and, thus could be turned into, a disciplinarily-correct physics concept (see Goodhew et al., 2019). In this way, I explore how students in technologically-rich learning environments may cooperate with other students through embodied interactions (Figure 21).

Figure 21. The emphasis of Theme 2 on the interactions between students.
The research question at the core of Theme 2 (RQ 2) is,

*How can students working in a digitally-rich environment be observed to make use of embodied, non-disciplinary meaning-making resources to reason in ways that are continuous with disciplinary-relevant aspects of a given physics task?*

As with Theme/RQ 1, I answer RQ 2 through an interpretivist analysis of a case study. Following a similar structure to Chapter 5, I first present the perspectives included in my analysis of the case study at hand, namely those of social semiotics, conversation analysis, and embodied cognition. I also review the relevant PER literature on kinesthetic/embodied learning activities (Section 6.1.1). I then discuss my selection of data (Section 6.1.2) and the style of transcription I used in my analysis and for publication of Paper III (Section 6.1.3). In order to evaluate the degree to which the participants’ meaning making is continuous with disciplinary physics, I then review the topic of orbital motion (Section 6.1.4), explain the specific question at the core of the case study of this paper, and present an answer to the question that aligns with the discipline of physics (Section 6.1.5). Following this, I am able to better present the analytical model I create through the combination of social semiotics/conversation analysis and embodied cognition (Section 6.1.6) before presenting the analysis of the case itself (Section 6.1.7). Finally, I synthesize and discuss my analysis of this particular pair of participants’ embodied meaning-making in Section 6.1.8.

### 6.1 Embodiment alongside DLEs (Paper III)

In Paper III, I take a closer look at how students might interact with one another in digitally-rich learning environments. To do so, I examine one particularly potent interaction that occurred between a pair or participants in the third dataset where the participants engaged in an *embodied dance* alongside a DLE.

As I have alluded to several times in this thesis, research shows that in addition to the familiar resources such as mathematical formalisms and spoken language, physics students also often recruit other resources such as gestures and manipulations of their surroundings to make meaning. For example, Gregorcic, Planinsic, et al. (2017) provide an analysis that shows how small groups of students using a DLE 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 embodied meaning-making resources to develop explanations of similar phenomena. To address this unexplored aspect, my investigation directly builds upon 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 a pair of participants’ non-disciplinary meaning-making resembles the latter, insofar as the participants came to not only describe what happens in orbital motion, but also explain why it happens the way it does.

To this end, in Paper III I present another case study of two participants as they explore a feature of orbital motion with the PhET simulation software, *My Solar System* (PhET Interactive Simulations, 2018), on an IWB. I show that the participants 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, et al., 2008 for an in-depth discussion of the topic). I show how the pair of participants 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 semiotic systems of talk, gesture, touch, and body position, but also the (typically) disciplinary semiotic systems 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 below.

### 6.1.1 The perspectives taken in Paper III

In Paper III, I make use of and adapt the perspectives of multimodal social semiotics (e.g., Airey & Linder, 2017), embodied cognition and conceptual
metaphor (e.g., Lakoff & Johnson, 1980), and kinesthetic/embodied learning activities (e.g., Scherr, Close, Close, et al., 2012).

In general, the perspectives taken in Paper III are tailored for valuing the multiplicity of ways by which individuals communicate beyond written and spoken language—that is, through a lens of multimodality (see Section 4.3). Recall from my discussion in Section 4.3.1 that, as part of an ‘embodied turn’ in research on language and social interaction, a growing number of scholars in education (both generally and within PER) are beginning to attend to an expanded picture of communication (e.g., M. Eriksson, 2020; M. Eriksson et al., 2019; Gregorcic, Planinsic, et al., 2017; Harrer, 2018; Samuelsson et al., 2019; Scherr, 2008; Scherr et al., 2013; Scherr, Close, Close, et al., 2012; Scherr, Close, McKagan, et al., 2012; Stephens & Clement, 2010; Volkwyn et al., 2019, 2018; Weliweriya et al., 2019, 2018). In Paper III, with my interest in how a pair of participants incorporated an embodied dance into their reasoning about binary stars, I take on multimodal perspectives that deal with how the body plays a crucial role in (1) how we communicate—in terms of social semiotics and combined with the overarching approach in my thesis of a conversation-analysis-type perspective—(2) how we think—in terms of embodied cognition and conceptual metaphor)—and (3) how we ultimately learn physics—in terms of kinesthetic/embodied learning activities.

**Multimodal social semiotics III**

In Section 4.3.1, I presented social semiotics as evidence of the ‘embodied turn’ within the field of linguistic research on language and social interaction as well as a recently-adopted perspective within PER. An important area of interest for social semiotics researchers in PER has been 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) relating to the task at hand (Airey, 2009; Airey & Linder, 2009, 2017; U. Eriksson, 2014; Fredlund, Airey, et al., 2015; Fredlund, Linder, et al., 2015a, 2015b). DRAs are “those aspects of physics concepts that have particular relevance for carrying out a specific task” (Fredlund, Airey, et al., 2015, p. 2). Among other things, studies using this perspective 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 discussed in Section 4.3.1, I depart from the typical implementations of social semiotics in PER. I examine how a pair of participants employ non-disciplinary resources while addressing DRAs of physics phenomena. To do so, I utilize and incorporate the analytic techniques inspired by conversation analysis, taking the participants’ 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., M. Eriksson et al., 2019; Samuelsson et al., 2019; Volkwyn et al., 2018), conversation analytic approaches (discussed in Section 4.3) tend to start with the resources used by individuals as they engage in conversation.

Paper III deals with the analysis of an interpersonal ‘dance.’ Thus, I pay attention to the (relatively uncommon) semiotic system of haptic-touch. Literature on haptic-touch, or simply haptics, can be found predominantly in the domains of human-computer interface research (see Section 2.3)—where the tools used to interact with computers have begun to incorporate resistive feedback or other sensorimotor stimuli (Jones et al., 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 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 et al., 2014; Flewitt et al., 2014; Jewitt et al., 2016). For the purposes of this thesis, I accept haptic-touch as a semiotic system insofar as I see it being used by participants while making meaning with one another.

**Embodied cognition and conceptual metaphor**

Mirroring the ‘embodied turn’ in research on language and social interaction (Section 4.3.1), the body has been viewed by many cognitive psychology scholars as an integral and noteworthy counterpart to the mind since the 1980s. A key example of this is found in the branch of cognitive science that is termed embodied cognition (see the review in Amin et al., 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 et al., 2015; Niebert & Gropengiesser, 2015; Niebert et al., 2012; Roth & Lawless, 2002a). 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). These models hold that, while there may be robust patterns of student responses in particular physics contexts (as much of the ‘misconceptions’ PER work holds, see Section 2.3), 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; Harrer, Flood, & Wittmann, 2013; Redish, 2004; Smith & Wittmann, 2008; Wittmann, 2002, 2006). 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; Smith et al., 1994). Another related framework is that of conceptual blending, which builds on the work of Fauconnier and Turner (1998) and which has received attention among 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 Theme 2 of this thesis, I take a perspective which accounts for a larger grain size of cognitive unit. As previously mentioned, a main impetus for carrying out the work in this theme was to meaningfully analyze the semiotic function of an enacted dance carried out by a pair of participants. 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 participants: 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 participants.

Therefore, in Paper III I choose to interpret the participants’ 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 participants’ metaphorical language which is grounded (Barsalou, 2008) in embodied experiences of 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, this perspective I take also resembles
the ‘resources framework’\textsuperscript{40} (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) 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 larger ‘chunks’ of cognition (as opposed to irreducible cognitive units). Still, by highlighting both the embodied nature of participants’ cognitive structures as well as the metaphorical nature by which they come to be used in the participants’ 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.

**Kinesthetic/embodied learning activities \textsuperscript{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 et al., 1998); or, they can push objects along surfaces with varying coefficients of friction to ‘feel’ the resistances those surfaces provide (Besson et al., 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., 1996): 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

\textsuperscript{40} The ‘resources’ of this cognitive perspective should not be conflated with the ‘semiotic resources’ from the social semiotic perspective used throughout Theme 2. While I use a cognitive model which does bear some resemblance to the framework with the former use of the term, my analysis in Paper III makes use of the term ‘resources’ in accordance with the latter.
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 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 & Planinišč, 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 et al., 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 et al., 2015; Enyedy et al., 2012; Johnson-Glenberg et al., 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 participants’ embodied engagement in a technology-rich learning environment.

6.1.2 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 dataset. This chunk of data involves a particular pair of participants, whom I refer to as Adam and Beth (pseudonyms adopted from Rådahl (2017)). 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), 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.

6.1.3 Transcription III
As I did with Paper I and II, I use portions of transcript—for this paper, translated by the research team from the participants’ native Swedish—as well as illustrations drawn from frames of the video data. The original analysis of this exchange was done 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 G. This transcript was included with Paper III as ‘supplementary data.’ Each line of the transcript is numbered (continuing the numbers from Section 5.2, for clarity) and labelled with the participant’s pseudonym who spoke or acted out the content of the line. The transcript comprises the participants’ 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, compiled in a style more typical of conversation analysis, is in Appendix G.

6.1.4 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 DLEs 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 Interactive Simulations, 2018) and the less-constrained DLE of Algodoo—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, et al., 2018; Gregorcic, Planinsic, et al., 2017; Rådahl, 2017). Students who are encouraged to explore orbital motion
with these DLEs have been shown to spontaneously engage with the topic in ways which mirror science-like exploration (Gregorcic, Planinsic, et al., 2017). 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. In this spirit, Gregorcic and Haglund (2018) have used the interpretive lens of conceptual blending to theorize how the combination of DLEs and IWB allow 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.

6.1.5 The orbital periods of binary stars

In Paper III, I study the 2.5-minute portion of Adam and Beth’s video-recorded conversation which precedes, comprises, and follows the Titanic-like dance. Before outlining the multi-perceptive analytic model used in this paper to analyze this dance, it is useful for me to first describe the physics topic that the two participants discussed from a disciplinary perspective. 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 participants are discussing the following question, which I refer to throughout the remainder of this chapter 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 serves as the participants’ focus for the 2.5-minutes clip that I analyze in Section 6.1.7. However, before I analyze the ways in which Adam and Beth came to answer the OP question, I first examine a disciplinary answer to this question in order to establish a 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 participants 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.41 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

41 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.
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 from the center of mass of the system (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 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 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 6.1.7, the participants’ 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:

1. DRA_1: the orbital phenomenon of the binary system involves the interaction of two bodies,
2. DRA_2: the two bodies are interacting reciprocally with one another,
3. DRA_3: the interaction of the bodies with one another is what determines their motion,
4. DRA_4: 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. DRA_1 and DRA_2 can be seen as facets of Newton’s Third Law, DRA_3 as a facet of Newton’s Second Law, and DRA_4 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.

6.1.6 My multi-perspective 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 22, as inspired by the practices of conversation analysis). I then interpret the embodied imagery associated with each of these utterances 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 22, as aligned with the perspective of embodied cognition). Since I am interested the degree to which the participants’ non-disciplinary communication relates

![Diagram of the multi-perspective analytic model used in Paper III](image)

Figure 22. A diagram of the multi-perspective analytic model used in Paper III (reproduced from Paper III under the CC BY 4.0 license).
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 22, 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 22), 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 participants’ dynamic, negotiated, and non-disciplinary meaning-making on the one hand (left half of Figure 22) with the more fixed system of disciplinary physics on the other (right half of Figure 22).

To illustrate the analytic model further, I use an example from my study. In the two-person, *Titanic*-esque dance, the two participants can be observed holding hands and leaning outward from each other (ostensibly, imagining to spin around). In performing this action, the participants are employing the semiotic resources of body position and haptic-touch. Thus, if I place the interaction in a diagram like Figure 22, these two semiotic resources occupy the leftmost column (Figure 23). While I temporarily defer what I acknowledge is a crucial explanation for the sake of illustrating my multi-perspective analytic model, I posit that these two semiotic resources combine to invoke an

![Figure 23. A diagram of my analysis for the example of 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 DRAs (middle right column) of the OP question, which in turn are aspects of three formal physics laws (right column) (reproduced from Paper III under the CC BY 4.0 license).](image)
embodied image of ROTATING IN A PARTNER DANCE (middle-left column, Figure 23). The ROTATING IN A PARTNER DANCE image is a multifaceted one and is likely the largest chunk of the mental elements that I identify under the category of ‘embodied imagery.’ Even in the initial posing of the dance, 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 participants, the dance can be seen as relating to all four DRAs for the question at hand (middle, Figure 23). As shown in the following analysis, the participants eventually elaborate on the ROTATING IN A PARTNER DANCE embodied image via other semiotic resources in order to highlight the relevance of specific aspects that I see as relating to particular DRAs. 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 participants’ informal communication appears be continuous with formal physics.

6.1.7 What I found (analysis) 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 4 of Chapter 3), which involves two larger (star-like) bodies and one smaller (planet-like) body. The participants 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 and then setting the masses of the two bodies equal to one another.

As the pair of participants 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 participants change the masses of the stars one last time Beth asks,

88 Beth: Why does it happen like that? [watching the IWB]
89 Adam: Because it’s for only two planets, so it’s—[points index fingers upward, Figure 25a] I mean, you must always have a counterforce toward where the other planet is.

90 Beth: Yeah. [looks at IWB]

91 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 89, where he can be seen involving an embodied image of RECIPROCITY OF INTERACTION, and (b) line 91, where he can be seen involving an embodied image of FORCED AROUND (reproduced from Paper III under the CC BY 4.0 license).

I first want to flag the way that Beth originally formulates the OP question, as it becomes relevant for tracking the progress of the participants’ interaction. When Beth asks the question ‘why does it happen like that?’ in line 88, I take it that she is inquiring into why the system of two stars behaves as it does.42 Though Beth specifically talks about the periods of each body in the time leading up to the OP question in line 88, she ends up using a phrasing which emphasizes the phenomenon as a whole. Given that the formal treatment of the

42 Beth uses the third-person singular pronoun ‘det’ (in English, ‘it’) as the subject of the question. Since referring to the system would entail the use of ‘det’ and referring to a planet would entail the use of ‘den’—due to the en/ett system for nouns in the Swedish language—I can exclude the possibility of her referring to a specific planet in her question.
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 88 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 6.1.5).

In his first attempt to answer Beth’s question, perhaps in response to how Beth had inquired about to the behavior of the phenomenon as a whole in line 88, 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 89 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 DRA 1, that the interaction requires two bodies.

Adam goes on in line 89 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 DRA 2, 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—which is used in Newton’s Law of Gravitation and is captured in DRA 4—i.e., that the interaction is attractive in nature.

In line 91, 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 ex-
plaining the stars’ motion. Here in line 91, 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 89 where she encourages Adam to continue, after line 91, 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 89 and 91.

**Segment 2: The dance**

When Beth does not respond to Adam’s utterance in line 91, 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 participants eventually enact twice.

92 **Adam:** If you and I were to rotate around like this [extends both hands to Beth, Figure 25a, left, next page]

93 **Beth:** Mhm. [grabs Adam’s hands, Figure 25a, right, next page]

94 **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 92-93). (b) Adam then acts out an unrealistic over-rotation in the dance context by scooting in his chair (line 94). This is the Titanic-esque dance that implies an embodied imagery of ROTATING IN A PARTNER DANCE (reproduced from Paper III under the CC BY 4.0 license).

In lines 92 and 94, 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 89 and 91, 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 participants, 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 86 and 91 with the haptic-touch and body position of the dance in lines 92 and 94 (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 that 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 94 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 94 shows him acting out the same counterfactual he introduced in line 91 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 systems of talk and gesture around the dance—along with a variation of his body position in relation to Beth— in a re-presentation of the counterfactual from line 91, 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 drawn to DRA-specific features within the ROTATING IN A PARTNER DANCE image through the inclusion of other semiotic systems. As Adam finishes his thought, he pauses to let Beth reply.

Indeed, purposeful variation of semiotic resources seems to be a critical feature of Adam’s more successful utterances (see Chapter 7).
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 95) (reproduced from Paper III under CC BY 4.0 license).

In line 95, 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 88, her utterance in line 95 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 participants 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 participants 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 participants might have linked their discussion with more formal terminology. Yet, 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 95, 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.

96 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]

97 Beth: Mhm. [stays in position with Adam, both of them holding hands with their arms extended]

98 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]

99 Beth: Yeaaah. [drops her hands and looks to the IWB]

Figure 27. (a) Adam reengages in the dance with Beth from a standing position (line 96, 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 96, right frame). (b) Adam over-rotates again (line 98, 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 98, right frame) (reproduced from Paper III under the CC BY 4.0 license).
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 91 and 94) 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 systems 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 physics students can and do coordinate their meaning making around non-persistent, experientially-shared embodied imagery.

After the second dance in lines 96 through 98, Beth responds with a satisfactory “Yeaaah” (line 99), 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, who, after watching the interaction of Adam and Beth with the dance, and in response to their exchange, pushes the two participants 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 participants 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.
Adam: I mean, they are directed toward each other [holds hands up to the IWB and follows both stars in orbit, pointing his pinky fingers toward each other, Figure 28, left] all the time. [repeats the motion with his index fingers]

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]

While Adam responds to the researcher’s question correctly, indicating central, inward-directed forces on the IWB (line 100), Beth incorrectly describes the forces as directed “away from each other” (line 101). 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 participants’ expressions suggest an embodied image of a SYMMETRIC PAIR (as in line 89), 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 DRA4. Conversely, Beth combines the symmetric pair image with an image of REPULSION.

102 Adam: No.

103 Beth: No? [steps back from the IWB]

104 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]

105 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 104, left frame). He then gestures in a circular motion while explaining that this is what keeps the stars going “around each other” (line 104, 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 105). In doing so, she involves the embodied image of ATTRACTION alongside the image of a SYMMETRIC PAIR (reproduced from Paper III under CC BY 4.0 license).
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 104), 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 DRA3. Perhaps surprisingly, the participants 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 105, 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.

106 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]
107 Beth: Toward each other. Okay.
108 Adam: So… then their forces [points his fingers together in air, Figure 30a, left, next page] can be represented [extends his hands toward Beth, Figure 30a, right, next page] as our hands, kinda.
109 Beth: Mm.
110 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]
111 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, next page]
112 Adam: Exactly.
113 Beth: Nice!
In this last section of transcript for Paper III, 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 95, 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 **DRA3**.

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, 29b, line 111). 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.\footnote{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.} 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 DRA\textsubscript{3}.

At this point of Adam and Beth’s interaction, I choose to end the analysis. The two participants 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 (next page), a table diagram which comprises the semiotic systems, embodied imagery, and DRAs associated with each line of Adam and Beth’s conversation for all three segments of video data analyzed above.

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 utterance\footnote{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.}). First in line 95 (Figure 26), I interpret...
Beth’s utterances as implying DRA$_1$, DRA$_2$, and DRA$_4$, since she mentions the two stars “holding each other” and gestures to the IWB suggesting an image of HOLDING TOGETHER. The researcher interjects between lines 99 and 100 and the participants are explicitly directed to consider the direction of the interaction between the two stars. Following the researcher’s question, Beth’s utterances imply DRA$_1$, DRA$_2$, and DRA$_4$ again as she gestures against the IWB with an image of a SYMMETRIC PAIR and ATTRACTION (line 105, Figure 29). Finally, as Beth relates her smaller size to the less massive star in the simulation (line 111, 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.

Figure 31 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 participants’ 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 systems within each cell (i.e., the number of semiotic systems used within each line that 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 94, 98, and 110. 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 systems—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 participant interactions like Figure 31 could be academically useful in future research for recognizing patterns in participants’ use of semiotic systems and/or evocation of embodied imagery.

6.1.8 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 Paper III as contributing to theoretical considerations within PER. The first 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. (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 participants use the content on the IWB screen as a backdrop for gestures. For example, the running simulation in line 100 and the paused simulation in line 104 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 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—e.g., the locally agreed-upon signs used in Energy Theater (Scherr et al., 2013) (such as ‘jazz hands’ for thermal energy)—as well as in conventionalized signs in formal discourse of physics—e.g., 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 6.1.1), I see the interaction of Adam and Beth as involving features of both categories. Similar to an ELA such as Energy Theater (Daane et al., 2014; Scherr et al., 2013; Scherr, Close, Close, et al., 2012; Scherr, Close, McKagan, et al., 2012), the two participants in the Paper III’s 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 participants (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, con-
versely, 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 student learning that 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*.

**The development of methodology**

While there does exists 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, Goodwin, & LeBaron, 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 multi-perspective analytic model—something which to my knowledge has not been done before. In doing so, I am able to make inferences about students’ reasoning⁴⁶ both in terms of non-disciplinary, embodied semiotic resources and also insofar as those resources relate to the discipline of physics. Paper III provides a new composite perspective 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.

**Fruitful embodiment**

In the 2.5 minutes of video data analyzed, Adam and Beth make use of non-disciplinary semiotic systems—including talk, gesture, body position, and

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⁴⁶ 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).
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 systems, educational value can be seen in the participants’ 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 \textit{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 participants are able to make use of it in their reasoning without actually completing a single turn of the dance during the interaction.

The non-disciplinary semiotic systems, particularly the non-verbal semiotic 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 \textit{mutually elaborate} one another. The data in Paper III provides an example of participants leveraging many distinct semiotic resources across different semiotic systems in their spontaneous (self-directed) interaction, which contribute to the construction of a communicational whole. 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.

\textbf{Generation of an enacted analogy}

As I discussed at the beginning of Section 6.1, 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 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). The literature suggests that this is 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 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 participants’ discussion that surrounds this analogy is certainly rich. In this way, Paper III highlights how non-disciplinary semiotic resources can be 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 a 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 6.1.7), 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 95 (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.

6.2 Embodiment as continuous with disciplinary physics III

In Paper III, I explored the extent to which a pair of participants’ embodied actions could be seen as continuous with disciplinary physics. That is, in the work comprising Theme 2, I sought to answer the question,

how can students working in a digitally-rich environment be observed to make use of embodied, non-disciplinary meaning-making resources to reason in ways that are continuous with disciplinary-relevant aspects of a given physics task?

For the purposes of examining the dance between Adam and Beth, I combined the perspectives of social semiotics/conversation analysis and embodied cognition into a single multi-perspective analytic model. This analytic model entailed me interpreting the multimodally-rich semiotic resources uttered by Adam and Beth as implying embodied imagery. It also entailed me generating
a disciplinary answer to the OP question in terms of four DRAs and three formal physics laws. Then, through an examination of how well the embodied imagery implied by Adam and Beth’s utterances aligned with the DRAs for the task at hand, I determined the extent to which the participants’ non-disciplinary meaning-making resources were continuous with disciplinary physics.

In Paper III, then, I illustrate how students’ coordinated use of non-disciplinary semiotic resources can support mechanistic reasoning about physical phenomena. I show how two students made use of an embodied analogy in the form of a partnered dance to formulate a response to a question about the orbits of binary stars. In doing so, I add to the growing collection of research that examines the diversity and richness of ways that students recruit meaning-making resources as they reason about physical phenomena (Section 4.3.1), as well as the discussions around cognitive models in physics learning. Moreover, while the technological affordances of the My Solar System simulation and the IWB were not the primary focus of my discussion during the analysis of this case study, I nevertheless provide a detailed account of a pair of participants working within and around a digitally-rich learning environment in disciplinally fruitful and previously unreported ways.

The activity in which Adam and Beth participated during this study was framed by the DLE and prompts given by the researcher. As discussed in Section 6.1.4, the My Solar System DLE 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). With an attention to the overlap of these two framings (technological and epistemological), I suggest that the broader learning environment was set up in a manner which encouraged the participants’ 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 Paper III, can tailor the facets of the learning environment (from Chapter 3) so as to support 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 that are 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. In using the terminology from Chapter 3, it is apparent that the interaction space facet of the broader learning environment around the DLE in Paper III was shaped to encourage embodiment-rich interactions through the inclusion of the IWB. By doing so, learning environments such as the one I have explored above may serve to enhance instructional approaches that take active learning (Meltzer & Thornton, 2012) and more specifically, collaborative active learning (D. W. Johnson & Johnson, 1999) as their guiding principles.

As a word of caution, it is worth pointing out that the semiotic system 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. Smith et al., 1980), and nationalities (McDaniel & Andersen, 1998) understandably 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 et al., 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.

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, participants 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, further explored in next chapter (Goodhew & Robertson, 2017; Rådahl, 2017; Robertson et al., 2015a, 2015). 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 in many ways. If Adam and Beth’s interaction had occurred in a classroom context with a teacher present, for example, the teacher could encourage these participants 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. This notion of responsive teaching alongside students’ use of DLEs is Theme 3 of this thesis.
7 Theme 3: The responsive role of the teacher

In Chapters 5 and 6, I presented Theme 1 and 2 of my thesis research, respectively. In this chapter, I present the third and final theme, Theme 3 (from Papers IV and V), which deals with the role of teacher(s) alongside students as they use less-constrained DLEs like Algodoo in small group work. In particular, I examine a teaching arrangement wherein physics teachers allow students to explore within less-constrained DLEs and responsively guide those students with situationally-appropriate reactions. In this way, both papers in this chapter involve the perspective of responsive teaching. Responsive teaching involves teachers foregrounding students’ ideas, explicitly recognizing their disciplinary value, and using them as starting points for classroom activity (Robertson, Atkins, Levin, & Richards, 2016). My use of responsive teaching in Theme 3 comprises my doctoral work around the ecosystem (expanded from the first half of my research and licentiate thesis; see Appendix A and Euler, 2019) that includes explicit attention to the role of the physics teacher in dynamically responding to the interactions of students in the presence of DLEs (Figure 32).

![Figure 32. The emphasis of Theme 3 on the interactions between students, teachers, and a DLE.](image-url)
In Paper IV, I provide practical recommendations for physics teachers about how to glean information during students’ use of DLEs and how to guide students who are using less-constrained DLEs toward the learning of specific physics content. Then in Paper V, I adopt a grounded-theory-type analytic perspective for multiple case studies and show that even when students are ‘freely exploring’ within less-constrained DLEs like Algodoo, their activity is always a near neighbor to a productive physics discussion. The research question at the core of this Theme 3 (RQ 3) is,

*How can teachers effectively interpret and guide students’ use of the less-constrained digital learning environment Algodoo such that those students engage in productive activities for their learning of physics?*

I answer this question in part through an interpretivist analysis of a case study (Paper IV) and in part through a grounded-theory-type, iterative coding of several case studies together (Paper V). As I have done in the preceding two chapters, I first present the perspectives taken in the two papers, respectively variation theory and grounded theory (Sections 7.1.1 and 7.2.1). For Paper V, my presentation of the perspective taken includes a discussion of the family of grounded theory methods. Then, I explain my selection of data (Sections 7.1.2 and 7.2.2) and the type of transcription used in analysis and publication (Sections 7.1.3 and 7.2.3). Finally, For Paper IV I present my analysis of the single case study in Section 7.1.4, followed by a synthesis and discussion of my analysis in Section 7.1.5. For Paper V, I present three activity types identified through the analysis of several case studies together and discuss possible productive physics discussion that can stem from them (Section 7.2.4). In Section 7.3, I bring the findings the two papers in Theme 3 together as I discuss the implications of responsive teaching alongside less-constrained DLEs such as Algodoo.

### 7.1 The use of variation theory in responsive teaching alongside DLEs (Paper IV)

I begin my discussion of Theme 3 with a presentation of my findings from Paper IV. In this paper, I explore a teaching arrangement wherein physics teachers responsively guide small groups of students as they use a less-constrained DLE in a mostly self-directed manner. My analysis leads to practical recommendations for physics teachers in terms of (1) how to glean useful information about students’ existing physics knowledge through observing how the students use the DLE and (2) how to responsively intervene so as to productively guide students toward the learning of particular physics content.
These recommendations stem from my use of the variation theory of learning—the relevant details of which are discussed below—as a lens for physics students’ use of DLEs (Ingerman et al., 2009).

The case study in Paper IV was motivated by my interest in exploring potential roles of the physics teacher alongside less-constrained DLEs like Algodoo. In watching the video data of participants using Algodoo without a specific prompt, it became evident to me that the researchers in the room were instinctively engaging in teaching practices that helped guide the participants towards the learning of specific physics content. This point was especially salient in the video data of the pair of participants that we had already studied in Papers I and II (one of the three pairs of participants from the first dataset). Thus, in seeking to explore the ways that teachers could make use of less-constrained DLEs like Algodoo, I chose in Paper IV to investigate this instinctually-occurring teaching arrangement where students use a less-constrained DLE in combination with the guidance of a responsive teacher (Robertson et al., 2016).

Responsive teaching involves teachers foregrounding students’ ideas, explicitly recognizing their disciplinary value, and using them as starting points for classroom activity (Robertson et al., 2016). For Paper IV, the guidance of a responsive teacher entails that students are initially given the choice to create freely within a less-constrained DLE and then the teacher selects relevant physics topics and phenomena from within the students’ creations as the topics of further discussion/unpacking. The key difference between most physics education approaches based on constrained DLEs and the one I examine in Paper IV is that the constraints which serve to corral students’ exploration toward certain concepts and/or procedures are in part imposed by a teacher, rather than exclusively by virtue of the DLE design. Arrangements involving the “complementary roles” (Tabak & Reiser, 1997) of DLEs and teachers have been studied previously in the context of CSCL. Though few in number, these studies have found that teachers can play a crucial role in augmenting the work that students do within DLEs (Tabak & Reiser, 1997). Such studies thus give credence to the notion that the scaffolding that is productive for students’ learning might be “distributed” (Puntambekar & Kolodner, 2005) by means of a “synergy” between DLE scaffolds and teacher scaffolds (Tabak, 2004).

In Paper IV, I provide examples of how the combination of a less-constrained DLE with responsive teacher guidance can empower students to (1) transition smoothly between physics topics, (2) engage creatively with physics content, and, importantly, (3) still develop conceptual understanding of relevant physics phenomena. In order for physics teachers to make productive use of less-constrained DLEs such as Algodoo, recommendations for optimally-responsive teacher guidance are warranted. I choose to adopt the perspective of variation theory to address this point. When applied to students’ use of DLEs such as Algodoo, variation theory is a useful perspective for analyzing
the ways in which students come to discern the critical aspects of physics phe-
nomena—and, thus, informs our recommendations for teacher interventions.

7.1.1 The perspective used in Paper IV

Below, I provide a brief background on what variation theory is and, specifi-
cally for Paper IV, the useful constructs from variation theory that lend them-
selves to my analysis.

The variation theory of learning

The variation theory of learning (or simply, variation theory) emerged in the
1990s from the Swedish research tradition of phenomenography (Marton &
Booth, 1997), the latter of which has sought to describe the qualitatively dif-
ferent ways that people experience or think about the world. As such, variation
theory is a perspective on learning that focuses on the manner in which people
come to perceive and discern things. While variation theory has been used to
explain the entire breadth of learning processes from children’s first percep-
tions of noticeable differences in their environments (e.g., Holmqvist et al.,
2014) to University students’ comprehension of complex fields of study (e.g.,
Marton, 2015; Marton & Pang, 2013), the analysis I conduct Paper IV calls
for the somewhat conservative use of three key variation theory concepts: (1)
contrast, (2) dimension of variation, and (3) relevance structure.

Contrast (change again a background of sameness)

The first concept from variation theory that I make use of in Paper IV is the
principle of contrast—or change against a background of sameness. Put
simply, this principle says that, in order to maximize the possibility of learning
about an aspect, one should experience that aspect vary against a fixed back-
ground (Fredlund, Airey, et al., 2015; Marton & Booth, 1997; Marton & Pang,
2013). This contrast principle should ring familiar to scientists, especially
since variable change against a background of sameness stands as a core tenant
in empirical investigations that call for the control of variables. What Marton
and other proponents of variation theory suggest, however, is that the system-
atic (though, often unconscious) variation of critical aspects underpins human
perception and learning from the earliest stages of childhood development
onward, not merely the intentional practices of the scientist engaged in exper-
imental work.

The emphasis on contrast is, perhaps, the key principle that differentiates
variation theory from other learning philosophies. A common approach advo-
cated for in teaching and textbooks is to provide students with “many exam-
iples in which the same concept is at work” (Bransford et al., 2000, p. 20).
However, the principle of contrast dictates that students would be better served
by being first shown a single context (background of sameness) within which
the desired concept varies (changes). Consider an example from physics
wherein students are expected to learn about the damping coefficient, \( \zeta \), in second order systems (adapted from Fraser & Linder, 2009). In the pursuit of maximizing the possibility of learning, it is less ideal to show students some examples of critically-damped shocks on a dirt bike, a critically-damped pointer in the dial of a moving coil ammeter, and a critically-damped RLC circuit in a band-pass filter. The changing backgrounds in these examples would be distracting for students with respect to the damping coefficient unless the students had already perceived what a damping coefficient of one (\( \zeta = 1 \)) means for the behavior of a system (i.e., they had already learned what ‘critically-damped’ means). Instead, variation theory holds that with regards to the possibility that the students perceive the desired aspect of damping, learning would be optimized by first showing the students an undamped, underdamped, critically-damped, and overdamped version of a single oscillatory system (i.e., the change of the damping coefficient against the fixed background of, for example, the same dirt bike).

**Dimension of variation**

Having established the importance of contrast (as a pattern of change against a background of sameness) for learning, the second concept from variation theory that I make use of in Paper IV is the notion of a dimension of variation. A dimension of variation is simply an aspect across which a range of values can be experienced (Fredlund, 2015; Häggström, 2008; Marton & Booth, 1997; Maunula, 2017). In the example used above, the damping coefficient, \( \zeta \), is a dimension of variation. Importantly for educators, a dimension of variation is an aspect which is ‘made possible to discern’ (Häggström, 2008, p. 57) through variation. Contrast is the suggested approach to varying things in order to maximize students’ discernment of a particular dimension of variation. In my use of ‘dimension of variation’ (henceforth, DoV), I refer in this paper to physical parameters such as velocity, density, and spring constant, which are involved in students’ exploration of **Algodoo**. The reason that we use the term, DoV, in this paper rather than more generic (or, perhaps, physics discipline-typical) alternatives such as ‘aspect’ or ‘parameter’ is threefold: (1) the label, DoV, foregrounds that variation is at the core of how these aspects or parameters are first discerned (and later used) by students and (2) the term, DoV, aligns well with how parameters are made accessible to the user in DLEs such as **Algodoo**—i.e., through a user’s manipulation of buttons and sliders to achieve variation, and (3) so as to not conflate the ‘D’ of DoVs with the main-

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47 Instances where the background changes behind a focal aspect are quite common in teaching and learning. Proponents of variation theory recognize the value of this type of variation—which they call **generalization** (as opposed to contrast)—but, importantly, see it as pedagogically useful only so long as it is preceded by contrast (Marton, 2015, p. 51).
stream physics use of ‘dimensions’ in reference to spatial and temporal dimensions (though, confusingly, spatial/temporal dimensions could certainly be interpreted as DoVs in the context of learning).

Proponents of variation theory have tended to track when and how certain DoVs are ‘opened up’ in the process of learning (i.e., discerned for the first time; see Marton, 2015; Marton & Booth, 1997; Watson & Mason, 2006) and how certain representations provide access to particular DoVs (Fredlund, Airey, et al., 2015; Fredlund, Linder, et al., 2015a). In Paper IV, I make use of the idea of ‘opening-up’ a DoV for when students first learn about a particular concept, but also depart from previous uses of variation theory in order to highlight how physics students can recruit already-learned DoVs. Specifically, I find it meaningful to track those instances when students choose to involve previously-discerned DoVs in their pursuit of a particular goal. Marton (2015) has acknowledged that students will “select a meaning among meanings” (p 41) when an aspect has been discerned previously, but the idea of tracking when and how learners involve previously-opened DoVs during problem solving or group interactions is to the best of my knowledge absent from the variation theory literature. Häggström (2008) and Maunula (2017) both examine how DoVs are incorporated into various student-teacher interactions, but choose to refer to any instance of a DoV’s appearance as it being ‘opened up.’ I take the position in Paper IV that there is an important qualitative difference between those instances where a DoV is discerned for the first time (i.e., opened up) and those instances where a previously-discerned DoV is incorporated (which I call ‘involved’). This distinction is especially pertinent for an analysis of students’ use of less-constrained DLEs, where the students must select from a relatively large collection of DoVs which may or may not be relevant for the task at hand. In such environments, the students’ choice of which DoVs to vary is, in itself, informative (continued below).

Relevance structure
The third concept from variation theory that I make use of in Paper IV is the construct of a relevance structure. From his research with physics students making predictions about torsion pendula, Székely (1950) found that some things come to be seen as being more relevant than others for a given task. Drawing on Székely’s work, Marton and Booth (1997) characterized this collection of things deemed relevant as a person’s relevance structure for a particular situation. A relevance structure is what is deemed to be needed (by the person) to appropriately deal with a situation at hand.

In paying attention to which DoVs students choose to involve in a given context (as described above), it is possible for teachers and researchers to gain insights into the relevance structures that students enact within certain contexts. This stems from the fact that, since less-constrained DLEs such as Algodoo host a wider array of parameters which may or may not be relevant to a particular phenomenon, the students’ choice of which parameters to vary
provides the observer with a sense of what those students deem to be relevant. I choose to refer to the relevance structures implied by students’ choice of DoVs as the students’ enacted relevance structures (see also M. Eriksson, 2020; M. Eriksson, et al., 2020).

For the purposes of Paper IV, my perspective informed by variation theory depicts physics DLEs—such as less constrained DLEs like Algodoo, but also constrained DLEs like PhET simulations, Physlets, and QuVis animations—as collections of physics DoVs. In the perspective I take in Paper IV, constrained DLEs provide only a select few DoVs at a time (a handful of sliders for key physics parameters, for example), while less-constrained DLEs host a relatively large collection of DoVs from which students can choose. My proposal in Paper IV is that physics teachers can pay particular attention during students’ exploration of DLEs to see when and how certain DoVs are varied. By doing so, teachers can gain insights into what students think matters within a given context (i.e., the students’ enacted relevance structures) and can also direct students toward opening up DoVs for the first time.

7.1.2 Selection of data IV
As mentioned prior, Paper IV makes use of a segment of video data from the first dataset, during which one of the pairs of participants were ‘freely exploring’ within Algodoo to get a better sense for the interface and function of the DLE. This specific case was chosen due to the richness I saw in the participants’ interactions with the DLE and, simultaneously, the instinctive actions of the researchers to responsively guide the participants toward specific physics content. Though the actions of the researchers were not conceived as such at the time, the intermittent feedback that the research team instinctively gave to the participants during the data collection sessions exemplifies the type of responsive guidance I recommend in Paper IV alongside students’ exploration of less-constrained DLEs.

7.1.3 Transcription IV
My analysis of the case in Paper IV involved first categorizing the overall progression of the session into four episodic parts and then identifying instances within each part where the participants meaningfully involved or opened up various DoVs. Continuing from the lines of transcript in Section 5.2.4 that used the PX label format for participants, I refer to the participants from Paper IV as Participant 8 (P8) and Participant 9 (P9). Additionally, to differentiate between the two researchers in the room I use the labels R1 and R2. As with the other three preceding papers in this thesis, the analysis below includes sections of written transcript as well as line illustrations drawn from particular frames of captured video—taken together to constitute a multimodal
re-representation of the audio and video data. Again, similar to the transcription conventions I used in Papers II and III, the transcript sections of Paper IV comprise the participants’ speech (written in plain or underlined text) and, when applicable, the participants’ nonverbal actions (written in [bracketed, italicized] text). Underlined text denotes an instance of speech that coincided with nonverbal activity (with the bracketed text immediately following the underlined text used to describe the nature of the nonverbal activity). Additionally, at times in my analysis, things occurred between the chunks of transcript shown in this chapter, but are not depicted in full detail. When this is the case, standalone bracketed text is used to transition back into the point where the transcript resumes. If no bracketed text precedes a section of transcript, it can be assumed that the new lines pick up immediately from where the last lines of transcript left off.

7.1.4 What I found (analysis) IV

The overall progression of the case presented here can be broken into four consecutive parts (Figure 33): in Part 1, the participants pursued—and successfully met—a self-set goal; in Part 2, the researchers asked the participants to reflect on what was done to meet that goal; in Part 3, the researchers gave the participants a new, related goal to build something based on the discussion in Part 2; and finally in Part 4, the researchers guided the participants toward learning about specific physics parameters with which the participants did not immediately show confidence. While the entire progression of this case is useful and interesting from the standpoint of physics teaching and PER, Parts 1 and 4 contain examples of the two central recommendations for teachers that emerged from my analysis of the entire session. Thus, below I provide a detailed analysis of these two parts and a summary of the other two. Specifically, with Part 1 I showcase how physics teachers can better understand students’ enacted relevance structures by observing which DoVs the students involve during their pursuit of a goal. With Part 4 I highlight how physics teachers can responsively guide students toward opening up a new DoV by encouraging them to make simpler digital constructions where the variational pattern of contrast is more readily experienceable for that DoV.

Figure 33. The four parts of the participants’ exploration of Algodoo. In Paper IV, my analysis focuses on the first and last of these (Part 1 and 4), as these two parts best highlight the two ways that variation theory is productive for physics teachers in interpreting and guiding students’ use of less-constrained DLEs (reproduced from Paper IV under the CC BY 4.0 license).
Part 1: Puncturing a sponge

In my analysis of Part 1, I explore an example of how, in pursuit of their own goals within Algodoo, the two participants choose to involve various DoVs and thus constitute an enacted releva nce structure. By tracking the DoVs which students involve, physics education researcher and physics teachers alike can construct a view of how students make sense of various disciplinary relevant aspects of the physics phenomena at hand.

Figure 34. Participant 8 (left) selects the ‘Spongify’ option from the dropdown Edit menu (inset, taken from a screenshot of Algodoo) as Participant 9 (right) looks on (reproduced from Paper IV under the CC BY 4.0 license).

Figure 35. A screenshot of the Algodoo interface with a recreation of the sponge ob- ject, selected to show the many internal objects making it up (reproduced from Paper IV under the CC BY 4.0 license).
I begin my analysis in Part 1 immediately after the participants have ‘spongi-fied’ an object using the ‘Spongify’ function in Algodoo’s dropdown Edit menu. As both students try out the buttons of the software, Participant 8 spon-gifies a roughly semi-circular object (Figure 34, previous page). This results in the internally-segmented shape (Figure 35, previous page)—referred to hereafter as ‘the sponge.’ It is useful to note that sponges in Algodoo are modelled as a collection of rigid (nonflexible) discs held together by elastic connectors (springs). With some limited technical help from the researchers, the participants draw a smaller object, lodge it inside the sponge, and then liquefy the smaller object to create a trapped pocket of red liquid. Once the pocket of liquid is created, Participant 8 begins drawing a shape to the left of the sponge and R1 asks, “What are you trying to do?”

114 P8: Uhh… trying to make an arrow and give it a velocity to see if it can pierce the spongified big pink blob [gestures toward the sponge]
115 R1: Ah okay!
116 R2: So, you can maybe try like a uh– a sharp thing–
117 P8: [draws an arrow shaped object as R2 is talking]
118 R2: Yeah, yeah, yeah and then maybe drop it from– or throw it in–
119 P8: [continuing to work as R2 talks, double taps the arrow object to bring up the dropdown menu] because I saw somewhere… [inspects the menu] add velocity. [selects the ‘Velocities’ submenu]

At this early stage of the participants’ exploration of Algodoo, the participants establish their own goal to puncture the sponge with a makeshift arrow. It is relevant to note that, though the goal of puncturing the sponge was first initiated by Participant 8, it is apparent from the exchange that follows that the goal was quickly taken up by Participant 9 as well. This goal emerges from the participants’ engagement with the DLE and, importantly, is not something imposed by the researchers externally. In terms of variation theory, my analysis judges the relevance of the DoVs involved by the participants based on whether or not the involvement of the DoVs moves the participants toward their own goal. For instance, Participant 8 mentions the desire to involve the arrow’s velocity (line 114) and subsequently locates the Velocities submenu (line 119). With this act, it is apparent that the participants are moving toward their goal, since the arrow-velocity DoV is, indeed, relevant for sending the arrow into the sponge. In what follows, the participants go beyond identifying that the arrow’s velocity is relevant to enact how they see the arrow’s velocity is relevant:

[after some technical difficulties with the Algodoo software crashing, the participants resume]

120 P8: Let’s just speed this one up. [drags the ‘Speed’ slider to the right] How much? [leaves finger on the slider and looks to P9]
121 P9: Full speed. [laughs]
The participants ‘give [the arrow] a velocity’ (line 114) by dragging the Speed slider to the right within the Velocities submenu, but the resulting motion has the wrong direction. It is worth noting that the participants opt to send the arrow into the sponge by imparting the arrow with an inherent velocity, rather than dropping it or throwing it as R2 suggests in passing (line 118). Imparting an arrow with a velocity is an unrealistic approach for making arrows move in the real world, so when employed within the domain of Algodoo, Participant 8’s choice here serves as another example of how students can recruit the mathematically-rich materials of a less-constrained DLE in unexpected, yet fruitful ways (see the discussion in Paper II).

This is the first observable instance of actual variation that the participants carry out for the purposes of meeting their goal. As such, the participants’ involvement of speed provides an indication that, for them, the speed of the arrow—though, not necessarily the velocity, as they had stated earlier—is relevant for puncturing the sponge. Since the participants’ manipulation of the Speed slider does not require them to explicitly attend to the direction of the arrow’s motion before hitting play, it is, at first, unclear from an outsider’s perspective whether the participants appreciate both speed and direction as relevant for the arrow’s motion before hitting play. However, once the play button is pushed, Algodoo unavoidably couples a direction to the speed by virtue of physical necessity. This inevitable projection of the arrow’s speed onto a specific direction highlights a particular representational affordance of Algodoo and other visually-dynamic DLEs: though speed and direction can be disambiguated from one another in an abstract sense (as they are in this sentence and in most physics classrooms), actual motion (represented in Algodoo or otherwise) will necessarily involve both speed and direction. The visual semiotic system of Algodoo forces the possible meanings of ‘speed’ in this case to be in a particular direction, just as a picture necessarily forces the possible meanings of ‘face’ to a particular set of facial features and/or hairstyles (again, as mentioned in Section 5.2, see the relevant discussion of transduction in Volkwyn et al., 2019). Thus, the participants are compelled to contend with the relevant DoV of direction as well as speed:
P8: [presses pause] Whoops.
R2: Wrong direction.
P8: Yeah, uhh… [presses the undo button and then opens up the Velocities submenu again; he finds the slider labelled ‘Velocity (X)’ and slides it from the left end to the right end] Like that. And… [examines the other sliders in the Velocities submenu; then starts moving the ‘Velocity (y)’ slider slightly to the left, only to stop himself] Is negative-y up or down? [leaves finger on slider]
R1: Down.

Here, from the perspective of variation theory, Participant 8 demonstrates an appreciation for the relevance of the DoVs of x- and y-velocity by involving them in the pursuit of the goal at hand. Importantly, Participant 8 outwardly considers both components of the arrow’s velocity and (correctly) chooses to update only the x-component and not the y-component. The option to edit the arrow’s direction of motion directly (i.e., irrespective of the speed) exists in the Velocities submenu via the ‘Angle’ slider and wheel (refer back to Figure 3, Section 3.4.1). Still, Participant 8 makes use of the Cartesian projection of velocity when redirecting the arrow’s motion. With each of these intricacies in mind, Participant 8’s updating of the arrow’s velocity gives even stronger credence to the developing notion that the participant(s) can meaningfully make use of the complex DoV of velocity in accordance with the conventions of the physics discipline—that is, a disciplinarily-correct version of velocity appears in the participants’ enacted relevance structure for the given context.

Following the adjustments made to the arrow’s velocity shown above (lines 124-127), the participants press the play button to run the simulation again. This time, the arrow is sent in the correct direction (into the sponge), but bounces off without successfully puncturing it. The participants pause Algodoo and proceed as follows.

[after correcting the arrow’s direction of flight]

P8: [taps undo] Can we add mass [opens the dropdown menu] to this one?
P9: [after both students visually scan the dropdown menu] Material maybe?
P8: [opens the Material submenu] Because, this one needs to be heavy otherwise it won’t go through, [slides the ‘Density’ slider all the way to the right, closes the menu, and then presses play again; this time, the impact of the arrow causes the sponge to deform considerably, but, still, no puncture occurs] Almost. Not pointy enough though.
P9: [taps undo and then selects the sponge] Decrease mass. [steps back from the IWB slightly and points at the sponge, indicating for P8 to take over]
P8: [now with more confidence, opens the Material submenu and moves the Density slider for the sponge to the left; he then closes the menu and presses play; the arrow flies into the sponge again, this time successfully lodging itself inside the sponge] (Figure 36, next page)
P9: Yes!
P8: That’s more like it! [P9 laughs and the two students stand for a while admiring their handiwork]
Here, the participants involve two more DoVs—namely, the arrow’s density and the sponge’s density—thereby signaling their appreciation that these DoVs are relevant for lodging the arrow into the sponge. In fact, the participants verbally announce that they want to “add mass” to the arrow (line 128) and “decrease mass” for the sponge (line 131), yet achieve both of these changes by means of the Density slider rather than the available ‘Mass’ slider for each. In doing so, the participants continue to not only involve DoVs which we would deem as relevant from a disciplinary perspective, but also to vary those DoVs in a manner which is appropriate for the specific context (i.e., such that they succeed in achieving their goal, shown in Figure 36). In this way, it is apparent that the participants’ enacted relevance structure comprises disciplinary physics concepts in two key ways: both (1) that particular parameters are relevant and also (2) how those parameters are relevant for the task at hand.

**Part 2: Unpacking the scene**

Following the participants’ success in lodging the arrow into the sponge, both researchers acknowledge the participants’ achievement: R2 says, “Nice! Well done,” and R1 says, “Did you actually just manage to… that’s awesome!” This kind of enthusiasm for the participants’ success signals to the participants that their ideas are valuable, even novel, in this context of doing physics. In what followed, the researchers take up the participants’ success as a worthwhile topic, asking the students to explain how they achieved their goal from **Part 1**. As the participants explain the changes that they made to get the arrow
to puncture the sponge, the researchers are provided with further insights into the participants’ reasoning processes (Charters, 2003) and a preliminary sense for the participants’ fluency in the terminology of physics (in this case, especially the disciplinary terms of speed, x-direction, and density). R1 notices that there is a part of the participants’ explanation of puncturing the sponge that could be further explored: while the participants used the term density in a satisfactory manner with regards to the arrow and its likelihood to puncture something, the participants’ responses make it less clear if they appreciate why the DoV of sponge density was relevant for their goal. Appreciating why changing the density of the complex sponge object changes its behavior requires an understanding of the way in which sponges are modeled in Algodoo.

R1 pursues this gap in the participants’ story by asking the participants to “say a few words” about why changing the density of the sponge mattered for their goal. As the conversation progresses, R1 encourages the participants to “show” what they mean in their explanation by manipulating the sponge itself in Algodoo. The participants are quick to suggest that the sponge is made of solid sub-objects connected together with “some kind of strings or springs.” By moving the Density slider for the sponge object in Algodoo, Participant 8 shows how, when the density of the sponge is altered, it changes the mass of the sub-objects without changing the strength of the spring connectors between them. Thus, the sponge, under the influence of gravity, sags apart (becomes “looser”) when its density is increased, and cinches up on itself when its density is decreased (Figure 37, next page).

Participant 9 drags a corner of the sponge away from the rest to demonstrate clearly how the object is composed of smaller chunks attached together (Figure 38, next page). R1 prompts the participants to incorporate formal vocabulary into their explanation, saying, “You mentioned some sort of spring. So, what are the things that determine how a spring behaves? Maybe you know a physics term that you use to describe springs?” The participants respond with “the spring constant!”

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48 This is not to say that absolute adherence to the ‘right physics terms’ is necessary, especially not immediately. Recall how I explored in Paper III the ways in which students are likely to use non-disciplinary discourse which is still valuable, perhaps necessary, to their reasoning about physics phenomena.
Figure 37. Participant 8 varies the density of the sponge via the Density slider in the dropdown menu (inset, taken from a screenshot of Algodoo). The sponge changes shape dynamically within the scene as the slider is moved, sagging downward as the density is increased and cinching up as the density is decreased (reproduced from Paper IV under the CC BY 4.0 license).

Figure 38. Participant 9 drags a corner of the sponge, which stretches the object apart and allows the participants to better perceive the internal components that Algodoo generates when an object is ‘spongified’ (reproduced from Paper IV under CC BY 4.0 license).
Part 3: Building something new (a sponge model)

Directly following the discussion of springs and spring constants, R1 gives the participants a new goal, secondary to the participants’ original goal of puncturing the sponge: “So what if you were to create your own sponge in *Algodoo*?” In response to this request, Participant 8 draws three small shapes connected by springs (i.e., a sponge model made up of three bodies). Once the participants build their three-body sponge model, they drag/throw the model around in *Algodoo* to compare its behavior to the behavior of the original spongified object (Figure 39).

![Figure 39. Participant 8 swings the participants’ three-body sponge model (magnified for the sake of clarity via inset) around in Algodoo, allowing the three-body model to fall to the ground and bounce in an effort to compare the behavior of their model to the behavior of the spongified object from earlier (reproduced from Paper IV under the CC BY 4.0 license).](image)

With their newly-built three-body sponge model, the participants then begin to explore the role that the properties of the spring-connectors play in the overall behavior of the sponge model. They double-tap one of the spring objects and the dropdown menu automatically opens to the “Springs” submenu (which happens by default in *Algodoo* when springs are double-tapped). In this submenu, the participants first change the target length of the springs (because the springs were relatively long compared to the size of the three bodies) and then change the spring constant.

**Part 3** provides an example of how teachers working alongside less-constrained DLEs can respond to students’ responses and set up new lines of in-
enquiry around students’ ideas (Robertson et al., 2016, 2015a). This is an instance where the unique affordances of less-constrained DLEs like Algodoo are readily apparent when compared to what is capable within other constrained DLEs in the teaching and learning of physics. Students can build things themselves in answer to requests from the teacher, but do so for topics (in our case, examining springs and sponge-models) which are only tangentially related to the starting point of the activity (to puncture a sponge with an arrow in Part 1). Allowing for students to transition between topical areas fluidly (within the same DLE) could help support students forming the view that physics topics are interconnected (Bagno et al., 2000; Elby, 2001; Hammer, 1994).

**Part 4: A new DoV (spring damping)**

In this final segment, the participants are encouraged by the researchers to open up a new DoV. To reiterate our use of the terminology, I use the phrase “open up a new DoV” to refer to an instance when student might be first experiencing and identifying a physics parameter as opposed to expanding the range of values for a DoV or involving a previously-opened DoV with which they are ostensibly familiar. In what follows, the researchers do the former for this cases’ participants in that they guide the participants toward opening up the DoV of spring damping.

Whereas, in Part 1, variation theory was helpful for gleaning useful information about the participants’ enacted relevance structures during their self-directed puncturing of the sponge, in this section I show how variation theory can inform how a physics teacher might intervene during students’ use of less-constrained DLEs like Algodoo to support learning of specific new concepts. In a past issue of this journal, Fredlund et al. (2015) recommend physics educators follow three steps in order to enhance the possibilities that students learn concepts based on variation theory: (1) identify the physics-relevant DoVs for a particular task, (2) select appropriate representations that provide access to those DoVs, and then (3) vary the DoVs within the selected representations. In less-constrained DLEs such as the one I explore throughout this thesis, students can create their own dynamic models in the place of carefully-prepared disciplinary representations. Thus, I reinterpret Fredlund et al. (2015) recommendation as follows for the context of less-constrained DLEs: physics teachers can (1) recognize a DoV worth focusing on during students’ use of a DLE, (2) guide students to construct their own systems and models that provide access to that DoV (i.e., such that the model is uncomplicated enough that the significance of the desired DoV can be discerned within the context), and then (3) encourage the students to vary the DoV. My analysis here in Part 4 follows how the researchers engage in such a process with Participants 8 and 9 for the DoV of spring damping.

I begin by looking at how R1 directs the participants’ attention toward the DoV of spring damping by virtue of the fact that it is one of three DoVs listed
in the Springs submenu. At this point in the session, the participants have already altered the other two DoVs in the submenu while manipulating their three-body sponge model—that is, both the spring constant and target length of the springs—but they have yet to indicate (through their words or actions) that they have noticed the slider for damping. R1 encourages the participants to look back into the Springs submenu for other constants and then, once damping is identified by name, asks the participants to explain their understanding of the term:

135  R1: Yeah what would [damping] be?
136  P8: That I actually don’t know. Could be, like, how… [holds hands out as if to pantomime an accordion, but then drops them] nah, that’s how—
137  P9: [overlapping] Is it some…
138  R1: Is there a way—
139  P9: [overlapping to finish his thought] …resistance to velocity or whatever it’s called? Resistance to velo— due to velocity or something. Don’t know. [shrugs]

In response to the R1’s question, “what would [damping] be?” (line 135), Participant 8 states that he does not know the term (line 136) and Participant 9 offers a somewhat hesitant definition that damping involves “resistance to velocity or whatever it is called” (line 139). Based on the participants’ answers, it is reasonable to assume that damping is a DoV with which the participants are less comfortable, especially when compared to the other DoVs involved in the session previously (e.g., speed/velocity, density, and spring constant). From the perspective of variation theory, then, damping appears as a good candidate DoV for the researchers to open up in the activity moving forward.

Following line 139, R1 encourages the participants to test Participant 9’s suggestion about damping as a “resistance to velocity.” He does so with the prompt, “Is there a way of testing that? . . . I mean, you can create other stuff or you can try stuff on that one [you have already created].” The participants choose to change the damping of the springs in their three-body sponge model, but in their attempt to reset the model to a baseline starting point, end up changing both the spring damping and spring constant. Participant 8 begins describing how the three-body sponge model “feels” different after these changes. However, after R1 points out that they changed two things at once, the participants quickly realize that the change in behavior cannot be attributed to the damping alone, since the value of more than one parameter was altered.

In what follows, the participants proceed with testing the impact of damping on their sponge model while holding the other parameters constant. As the three-body sponge model is a complex entity, however, it is difficult for the participants to discern the impact of varying the damping DoV on the behavior of the sponge model overall. The participants end up using vague words like “twitchy” to describe the new sponge with low damping. Eventually, R1 suggests that the participants construct a model in Algodoo which is simpler than
the three-body sponge model so that they can more directly test what spring damping means: he says, “is there a way that you could test what damping means in a system that is not as complicated as this. . . umm, sponge that you created?”

In response to R1’s suggestion, the participants clear the Algodoo scene and create a new, somewhat-simpler model with a spring and a square which can slide horizontally on the ground. Participant 8 suggests that they send a circle rolling into the square to see how the spring responds when given various damping values, claiming that he thinks “damping means how much you can [press a spring] together in itself.” After the participants are given some time to work with this new model (ultimately, they struggle with how to make the circle compress the spring in the desired way), R1 asks the participants how Participant 8’s suggested definition for damping differs from that of a spring constant. Participant 9 responds that he thinks damping has to do with velocity, “similar to air drag, but for a spring instead” (returning to, and reiterating, his original answer given in line 139). R1 notices that the new model built by the participants is still too complex for the participants to experience the role of the spring damping DoV. R1 suggests that the participants think of a way to test if Participant 9’s velocity-related suggestion is correct.

[after trying to explore damping with the horizontal system of a spring, square, and circle]

140  R1:  So, what if you think about everyday situations. [the students turn away from the board to face R1] Where would that come into… uhh into play? The properties of springs.

141  P8:  Suspensions? In cars, I think?

142  R1:  Okay, so… can you– can you explain what a what a suspension with a big damping and a suspension with a low damping would look like? How would the car behave in one or the other? [P8 turns back to the board to edit the velocity of objects in Algodoo, then stops as P9 starts answering]

143  P9:  With the big susp– uhh… damping, it would be quite [holds hands apart from one another vertically, as if holding a water bottle by the top and bottom] stiff. [brings hands together quickly, but stops short of them touching] It would push a bit and then stop. [repeats the vertical ‘compressing’ motion, slower this time] The whole process of, uhh… [moves top hand up and down as he searches for the word]…oscillating! Oscillating would be quite slow in our experiment. [resumes the vertical compressing gesture] While, a spring with low damping, [beat gestures] it would oscillate rather quickly instead. [repeats the vertical compression gesture but moves his upper hand up and down several times at a fast pace]

Here, R1 encourages the participants to externalize some explanation of what ‘big damping’ and “low damping” might look like within a real-world example (car suspensions). Participant 9’s answer in line 143 includes the idea of a spring stopping when highly-damped, but also relates damping with speed of oscillation. Participant 9 also employs the word “oscillating,” which R1 uses to urge the participants to test out Participant 9’s suggestion about damping:
R1: Mhm... Now what if you make an oscillator? How do you make an oscillator? With a spring in here— [as R1 is asking these questions, P8 turns back to the IWB and resumes tinkering with the spring setup on the IWB]

P9: [overlapping] The easy way? In here?

R1: Or– or anywhere, really?

P9: We could, uhh, hang a spring. Add a weight— attach a weight to a spring [points to a spot above the ground in Algodoo near the top of the IWB] and give it some velocity downwards. [cups to point downward and then moves arm down in front of the IWB] It should– it should start… oscillating. [forms hand into a blade and gestures back upward along the IWB]

By this point, R1 has led the participants to come up with the idea for a model in Algodoo which is simple enough that the participants can likely open up the DoV of spring damping (i.e., that the variational contrast of the damping DoV is discernible). Importantly, the participants are maintaining some level of ownership of the process still, since they continue to come up with the details of the next step of action. R1 simply encourages them to think of taking certain steps which are, in turn, useful for progressing toward opening up the DoV in concern. Following the segment of transcript above, the participants hang a box from a spring in Algodoo and make it oscillate for various values of spring damping (Figure 40, next page). At one point, Participant 9 moves the damping slider all the way to the right to the maximum value. This creates the condition of an overdamped oscillator:

[after the participants have tried several values of spring damping with their oscillator]

P8: [drags the box away from the spring, releasing it to see how the damped spring will react] Yeah.

P9: Yeah.

P8: It’s like eeeewww [pitches voice downward and gestures like he is compressing an accordion]

Participant 8 impersonates the behavior of the (overdamped) oscillator by voicing a downward-warping sound effect and enacting a compression-like gesture. It is apparent at this time that the participants are experiencing the behavior of an overdamped oscillator, maybe even viscerally so, such that the DoV of spring damping is being opened up (especially for Participant 8).

49 The ‘Damping’ slider in Algodoo actually allows users to alter the viscous spring damping parameter. When a spring is generated in Algodoo, the numerical scale of the damping slider is automatically set so that the middle position of the slider (and, thus, the displayed ‘Damping’ value) corresponds to the spring being critically damped. In a peculiarity of the Algodoo code, if the mass of a system containing springs is changed without changing any of the spring parameters (i.e. without moving any of sliders for the spring constant, damping, or target length), then the damping slider is not rescaled. As such, the value ‘1’ on the slider will no longer correspond to the system being critically damped.

50 Showing yet again, an example of the semi-formality of Algodoo.
Though informal in nature, Participant 8’s embodied action in line 150 aligns well with a critical aspect of overdamped oscillators, namely, that the mass (box) returns to the rest position without oscillating. In Chapter 6 (Paper III), I showed that non-disciplinary utterances such as this, which correspond well with the core ideas of a disciplinary physics concept without necessarily using the discipline’s agreed-upon conventions outright, can be valuable in students’ development of explanatory and mechanistic models of phenomena (see also, Gregorcic, Planinsic, et al., 2017). As was discussed in Part 2 and Part 3 of this case’s analysis, one way to build on students’ use of such language is to encourage them to later incorporate the disciplinary terminology after the non-disciplinary utterance has communicated the main thrust of what was originally experienced. Following Participant 8’s impersonation of the overdamped oscillator, R2 encourages the participants to try out other terminology with the question “what other words could you use to describe the spring based on this parameter?”:

151 P8: Strange… [laughs] in a sense.
152 P9: Stiff?
153 R1: But you could– you could– in a sense, you could– yeah. You could use stiff also in another way, right?
154 P9: Mhm. With the spring constant, yes.
155 R1: So, it’s good that we have two words, [laughs] because they mean different stuff apparently.
Here, R1 explains how the colloquial term, stiff, is ambiguous in whether it refers to a large spring constant or a large damping. In doing so, R1 helps motivate the need for the disciplinary terminology for the participants. Furthermore, by the end of this interaction, the researchers finally confirm that idea of damping is related to the velocity of a spring’s oscillation. It should be noted here that, while this was the end of the damping discussion in our data, an ideal teacher would likely do well to spend more time reflecting on what these participants think damping means. A core recommendation of variation theory is for learners to take newly opened up DoVs—which are first experienced through contrast in simplified models for the sake of discernment—and embed them in broader, more complex systems to better contextualize how the DoVs play a role alongside other DoVs (see Marton’s (2015, p. 50) discussion of “generalization” and “fusion”). In the case presented here, it would have been useful for the participants to return back to their three-body sponge model, for example, after having opened up the DoV of spring damping. Nonetheless, at the time of data collection, the researchers in the room were justifiably content with the fact that this session—which started as the participants’ self-directed exploration of how to puncture a spongified shape in Algodoo—had naturally led to the pair of participants learning more about a new physics parameter. Thus, such a recontextualization of the newly opened-up DoV did not occur.

7.1.3 Synthesis and discussion of this case

In the analysis above, I highlight two key ways in which variation theory can inform responsive teaching alongside the participants’ use of the less-constrained DLE, Algodoo. In Part 1, I show how the pair of participants involved DoVs with which they had previous experience, thereby displaying an enacted relevance structure for the respective teacher/researcher. Attending to students’ enacted relevance structures in less-constrained DLEs—which by virtue of the environments’ design present users with a collection of DoVs to be varied that may or may not be relevant for the context at hand—corresponds well with Sayre et al.’s (2004) analytic focus on student reasoning in “nearly-novel” situations. In nearly novel situations, physics students have “studied all the relevant physics principles but have not previously synthesized the ideas in a specific setting” (p. 101). Nearly-novel situations are particularly
apt for providing teachers/researchers with insight into “issues of transfer of knowledge, coherence of understanding, and student epistemologies and metacognitive skills,” among other things, especially insofar as they “[force] students in an uncharted area outside established conceptions but still near many resources” (Sayre et al., 2004, p. 101). My analysis of Part 1 above provides the interested physics teacher/researcher with a practical example of how to meaningfully observe students engaged in nearly-novel situations within less-constrained DLEs. I recommend that teachers pay attention to when and how students involve various DoVs (i.e., the physics parameters made manipulable by Algodoo) during pursuit of self-set goals. For the variation theory-informed teacher/researcher who utilizes less-constrained DLEs in this way, students’ playful exploration can materialize as fertile sequences of pedagogically-useful variations upon which future scientific inquiry can be built.

In Part 4, I illustrate how a physics teacher can guide students toward learning about a new physics parameter (i.e., open up a new DoV) within less-constrained DLEs by leading students toward building simple models that make the contrast of that parameter more directly experienceable. Especially when the participants demonstrated a lack of confidence in the meaning of certain DoVs (e.g., line 136), the researchers were able to responsively propose directed goals to the participants through questions like “is there a way of testing that?” (following line 139) or “how do you make [something like that]?” (line 144). In engaging in this type of responsive practice, physics teachers can successively steer students toward the construction of more productive models for the discernment of specific physics DoVs. While aiming to experience the meaning of a particular DoV, students may naturally tend to vary more than one DoV at a time or create overly-complicated models which obscure the role of the DoV within complex contexts (as seen with the participants of Paper IV before line 140). However, while a more conventional PER-informed approach utilizing constrained DLEs would likely dictate that the digital environment itself be “cleaned up” so as to minimize the possibility of students taking such detours, the approach featured in Paper IV would not only allow students to be guided toward an optimally-simplified model through responsive feedback, but it would also allow the students to experience the messy, non-linear progression of scientific exploration. This has the potential, in turn, to demonstrate to students the value of simplified models in the practice of ‘doing physics.’ When compared to existing variation theory literature, the teacher intervention in Part 4 can be seen as a responsively-improvised rendition of an instructional technique where teachers (1) recognize a DoV worth focusing on during students’ use of a DLE, (2) guide students to construct their own systems and models that provide access to that DoV (i.e., such that the model is uncomplicated enough that the significance of the desired DoV can be discerned within the context), and then (3) encourage the students to vary the DoV (adapted from Fredlund, Airey, et al., 2015).
While, for the sake of brevity, the analyses of Part 1 and Part 4 are the only parts presented in depth, it is worthwhile here for me to briefly comment on the entire session involved in Paper IV. First, it is important to note that the progression from Parts 1-4 (shown in Figure 34) is not meant to convey a prescribed sequence that students should follow. Instead, it is a description of what took place in this particular case study. For one, as we mention above, the conventional recommendation of variation theory would be for something of a fifth part to have followed after Part 4. In such a fifth part, participants could have re-contextualized the DoV of damping within more complicated contexts. In fact, teachers could reasonably choose any of the four parts seen in our data as a starting point for an Algodoo-based activity: as per the aim of Part 2, students could initially be given a constructed scene to unpack (e.g., Gregorcic, 2015a; Gregorcic, Planinsic, et al., 2017); as per Part 3, students could be explicitly asked to build a specific construction (e.g., Paper II); or, as per Part 4, students could initially be directed toward learning about specific parameters (Vliora, Mouzakis, & Kalogiannakis, 2018). As suggested from the discussion in Chapter 3, these different implementations of the DLE might have the effect of shifting the functional facet profile of Algodoo. Nonetheless, this pronounced flexibility is one of the unique benefits to less-constrained DLEs like Algodoo: less-constrained DLEs allow for a diversity of activity type—and, importantly, for smooth transitions between each of these activity types—within the same DLE.

Second, despite my use of the ‘less-constrained’ framing in this paper, it is important to reiterate that each of the four parts of the session presented above did, in fact, involve constraints on the students’ activity to different degrees from the broader learning environment and the DLE itself. For example, there were conversational constraints imposed by the researchers (acting to an extent as task managers) in response to the students’ exploration in Part 4. The Algodoo DLE itself also carried with it a structure that constrained the students to within a ballpark of useful phenomena. That is, the collection of variables in Algodoo are on-the-whole relevant for physics phenomena, so students can be anticipated to experience (and potentially discern) some parameters during their exploration which are germane for the discipline of physics. Thus, less-constrained DLEs like Algodoo may provide a productive balance between messiness and structure that encourages students to enact science-like behaviors while staying creative and intrinsically-motivated. This line of thinking is something I went on to explore further in Paper V.
7.2 The productivity of messing about in *Algodoo* (Paper V)

Paper V came about through my collaboration with a master’s student to examine patterns in how students use *Algodoo* for the first time (Prytz, 2019). The goal with Paper V was to show how, even when students are allowed to explore within *Algodoo* without a prompt to look at something specific, their exploration can be construed as productive to the responsive physics teacher. Thus, in combination with Paper IV, a teacher might see the potential for including less-constrained DLEs like in their teaching practice and be better prepared for what to expect during students’ engagement with the software.

Despite my particular interest in responsive teaching based on its prevalence in my data, it is worth mentioning that a physics teacher who includes a less-constrained DLE such as *Algodoo* in their repertoire of curricular materials can choose to implement the software in a range of ways. At one extreme, a teacher can use *Algodoo* as a means for students to engage with specific physics content in directed tasks. In this approach, students can use *Algodoo* to explore a range of physics topics, from projectile motion (Bengtz, 2018) to Kepler’s laws (Gregorcic, 2015a), kinetic gas theory (Östlund, 2018), and the refraction of light (Vliora et al., 2018) – all within the same DLE. This topic-specific use of a less-constrained software more closely resembles the productively controlled approach behind many *phenomenaria*-functioning DLEs such as the simulations (as discussed in Section 3.3). Nonetheless, as I will discuss further at the end of this chapter, while there is a resemblance in scope between a topically-focused use of less-constrained DLEs and the typical use of constrained DLEs, it should be pointed out that in the case of the former, many of the constraints are imposed by the broader learning environment (especially the teacher in regards to the *task manager* facet) rather than through the imposed limitations of the DLE itself.

At the opposite extreme of potential implementations of less-constrained DLEs like *Algodoo*, a physics teacher can choose to take more student-directed approach like that demonstrated in Paper IV. In such an arrangement, a teacher can refrain from selecting specific topics, allowing students to explore the software for themselves and responding to the students’ exploration at opportune points. Such a student-directed approach may intuitively seem too unfocused to be worthwhile for the teaching and learning of physics. However, as shown above in Paper IV and explored further in Paper V, students’ self-directed exploration has several unique, if unanticipated, affordances for physics education.

In Paper V, I describe three types of activities identified while observing students’ self-directed use of *Algodoo* and explain how each activity type has the potential to be productively leveraged by a physics teacher. Among other things, I show that, by allowing students to creatively explore within tool-rich physics environments such as *Algodoo*, physics teachers can springboard into
a range of relevant discussions while supporting and valuing the agency and divergent thinking of students.

7.2.1 The perspective taken in Paper V

Though being the final paper of my thesis, Paper V is the first and only paper where I depart from the conversation-analysis-inspired, stand-alone case studies of the previous four papers. Instead, I employ a grounded-theory-type perspective (Glaser & Strauss, 1967). Below, I discuss the background of this type of perspective and before presenting how this perspective was applied to find patterns across several cases of video data of participants ‘freely exploring’ within Algodoo.

The grounded theory ‘family of methods’

Grounded theory is an ‘inductive’ method of research, first proposed by Glaser and Strauss in 1967 (Bryant & Charmaz, 2007), whose adherents generally proponent to analyze data without a pre-formed hypothesis. Instead, data are grouped and/or coded according to perceived similarities and then patterns are searched for amongst the list of codes. Glaser and Strauss (1967) originally created grounded theory in hopes of establishing a scientifically rigorous methodology for qualitative research.

According to Bryant and Charmaz (2007) grounded theory now holds the prolific position as the most widely-cited method in the social science (from Black, 2009). Due to the dissimilarities between the multitudes of studies that apply the ‘grounded theory’ label to their work, Bryant and Charmaz suggest that the method would be better cast as a ‘family of methods’ bearing similarities but never the same common set of characteristics (Black, 2009; Bryant & Charmaz, 2007). As such researchers who utilize a grounded-theory-type method of analysis should better define their methodology by being transparent about the specifics of their approach (Locke, 2001). For one, researchers using grounded-theory-type methods should acknowledge that “the [grounded] theories do not reside in the data waiting around to excavated” (Prytz, 2019, p. 11), and thus endeavor to provide sufficient background on their own perspectives and backgrounds in order to contextualize their interpretations.

In the spirit of analyzing data without preconceived hypotheses, many research projects based on grounded-theory-type methods typically include the iterative coding and qualitative pattern detection at the beginning of the projects. In this thesis, I have opted to do the opposite, carrying out the grounded-theory-type portion of my research at the chronological end of my doctoral work. However, as explained in the front matter of this thesis, the original pass of coding and categorization of the video data was done by a master’s student I co-supervised, Christopher Prytz (2019). In so doing, the preconceived notions of less-constrained DLEs, productive embodiment, and semi-formality I
had built up through the course of my thesis work were not imposed on the data from the outset. Thus, Prytz’s perspective and background are the most germane to review in justifying the grounded-theory-type method applied to the various segments of video from the first and fourth datasets of this thesis. The following is taken from Prytz’s master’s thesis where he discusses his perspective, biases, and the iterations of the analysis process:

I initialized the study without the intent to test any pre-formulated hypothesis and without any pre-formulated specific questions of research, other than the general question of how students utilize Algodoo. The aim was not to verify or dismiss any pre-existing theory but to, hopefully, come up with findings of my own that stemmed from the data. I tried to enter the study with as much of a clean slate [tabula rasa] as possible, however, to say that I entered without any biases or preconceptions would be dishonest as a complete elimination of bias, for anyone, is unachievable. The most prominent potential bias might be my reading of Papert’s (1980) Mindstorms. Nonetheless, as a result, I had no idea of my potential findings prior to the first analysis. Regarding the analysis, I went through multiple iterations of coding, transcribing what I saw and heard in the recordings.

I started my analysis by writing down what I found interesting. I transcribed some of what the students said, the gestures they used, the tools and properties of the software that the students explored, the specific constructions of the students (for example, the construction of a space-rocket) and more. This was my first iteration of coding. As I narrowed down the scope of the study to only include the time the students freely explored the software, I became more detailed in my transcriptions. By taking handwritten notes, I could easily color-code my transcriptions by each actor (in each case, the actors being two students and one or two researchers). I also divided the paper into four columns one [sic] for the quotation of each actor and one for what was done in the software. Once I had some initial coding, I tried to divide the coding into clearer sections and to give each section some brief summary or labelling of its content. This resulted in the three types of activities […]

(Prytz, 2019, p. 13)

The codes and categorizations were collaboratively modified with Prytz, myself, and Bor Gregorcic (my main supervisor). Still, but utilizing Prytz’s relatively non-predisposed perspective in the grounded-theory-type analysis, I can trust that the three category types were not perceived based on my findings from the first part of my doctoral work. The analysis conducted by Prytz was then collaboratively expanded upon in the production of Paper V. Though different in approach in many ways to the case-oriented methodology of the first four papers of this thesis, the grounded-theory-type perspective used in the Paper V stands up to the same interpretivist criteria for trustworthiness (see Section 4.4.1).
7.2.2 Selection of data

The goal with Paper V was to apply a grounded-theory-type method of analysis to sessions from my data where participants were exploring a less-constrained DLE for the first time. The first and fourth dataset included video of seven pairs of participants familiarizing themselves with Algodoo and, as such, this data was selected for analysis. In contrast with the other papers of this thesis, I do not include any transcripts from the iterative coding done for Paper V, focusing instead on the three activity types identified through the analysis. For a more complete account of Prytz arrived at the codes he did, including scans of his hand-written notes during coding and categorization, I refer the reader to his master’s thesis and the appendices therein (Prytz, 2019).

7.2.3 What was found (analysis and discussion)

In Paper V, three activity types that students are likely to engage in while ‘getting to know’ less-constrained DLEs like Algodoo were identified. We chose to refer to them as (1) exploration of the software fundamentals, (2) testing and contrasting, and (3) engineering. Below, I present each of these activity types along with their potential relevance for the teaching and learning of physics.

**Activity type 1: Exploration of the software fundamentals**

During the first activity type, which I refer to as exploration of the software fundamentals, participants investigated the tools and functions of Algodoo. This activity type was characterized by the participants familiarizing themselves with Algodoo’s buttons, toolbars, and drop-down menus (see Figure 41, next page) in order to develop a sense for the basics of how the software is operated. The participants’ exploration of the software fundamentals tended to be (outwardly) chaotic, exemplified by the participants shifting their focus between the many features housed in Algodoo. Especially when the people using Algodoo are new users, this first activity type is the behavior which physics teachers should expect to see chronologically first (merely due to the unfamiliarity of every aspect of the DLE). Additionally, due to the high number of features made available in Algodoo, participants frequently returned to this activity type throughout their exploration as they discovered new functionalities of the DLE.

Students’ exploration of the software fundamentals can be productive for the physics teacher insofar as students naturally uncover new physics parameters. While students ‘poke around’ in the Algodoo software, they interact with the buttons and sliders corresponding to various parameters that tend to be relevant to the discipline of physics (e.g., restitution, damping, speed/velocity, gravity, kinetic energy, and so on). Depending on the students’ familiarity with the formalisms of physics, the parameters encountered in the interface of
Algodoo will be more or less recognizable to the students. A responsive physics teacher can notice which parameters seem to be less-recognized by students and encourage those students to further investigate those parameters unfamiliar to them. The researchers guiding students toward spring damping in Part 4 of Section 7.1.4 is a prime example of this type of responsive teaching.

Figure 41. Two examples of the Edit drop-down menus that participants tend to familiarize themselves with in Algodoo during the first activity type, ‘Exploration of the software fundamentals.’ On the left, the Edit menu is shown open to the Material submenu, where users can vary the density, mass, coefficient of friction, etc. for the object(s) selected. On the right, the Edit menu is shown open to the Springs submenu, where users can vary the spring constant, viscous damping parameter, and target length of spring(s) (reproduced from Paper V under the CC BY 4.0 license).

Activity type 2: Testing and contrasting

In the second activity type, which I call testing and contrasting, the participants in my data explored how well the physics engine of Algodoo matched the real world. Participants tended to construct ‘classic’ physics scenarios within the software to ensure that the DLE behaved as it should (e.g., dropping two objects from the same height to demonstrate the acceleration due to gravity) or they create simple tests to determine if the DLE allows for certain complexities of physics interactions. For example, Algodoo allows the user to assign material presets such as glass, wood, steel, etc. to objects, which correspond to certain configurations of the objects’ density, friction properties, restitution, and refractive index. One pair of participants dropped a square onto a thin rectangle given the material preset of glass to see if glass objects would shatter in Algodoo (Figure 42, next page). In general, I have found that students engage in testing and contrasting to check ‘how far’ they can go within the software.
For the physics teacher, testing and contrasting activities can be productive in that they can be leveraged to highlight the role of modeling in physics (Etkina, Warren, et al., 2006; Hestenes, 1992; see also, the discussion around semi-formal modeling in Chapter 5). For example, in the case shown in Figure 42 involving the ‘glass’ rectangle, a physics teacher could use that pair of participants’ testing experiment to discuss how we use and test models in physics (Hestenes, 1992). Beyond supporting discussions of physics modeling, students’ testing and contrasting activities can serve as the backdrop for introductory discussions around the use of computer simulations in modern science (Greca et al., 2014).

**Activity type 3: Engineering**

In the third activity type, which I refer to as engineering, participants tended to prototype machines in the pursuit of self-determined goals within Algodoo. For example, several of the participants in my data constructed a simple car and, after getting their car rolling, created obstacles such as a small hill for the car to traverse (Figure 43, next page). In doing so, these participants were motivated to explore the role of friction, torque, etc. in the context of a car climbing a hill. In many cases, the participants’ impetus to construct machines
came during their noticing a specific feature of *Algodoo* in their *exploration of the software fundamentals* (activity type 1). After finding *Algodoo*’s ‘thruster’ tool, for instance, potential student users of *Algodoo* might quickly transition into building a rocket. A salient feature of *engineering* activities in my data was the participants’ modification of their machines in pursuit of self-determined goals. In this way, the participants’ *engineering* activities seemed to involve iterative loops wherein they designed, tested, and challenged various prototypes.

Figure 43. A screenshot of the kind of machine typically created by students in *Algodoo*—again, recreated by me for Paper V—as they engage in the third activity type, *engineering*. A simple car consisting of a rectangular ‘body’ and two circular ‘wheels’ (fitted with motor-driven axels) drives up an angular obstacle also created by the participants. In achieving the goal of driving their simple car up and over this obstacle, participants engage with the coefficient of friction of the wheels/ramp and the torques applied to the motor-driven axels, among other things (reproduced from Paper V under the CC BY 4.0 license).

Physics students’ *engineering* activities may be useful for the physics classroom in that they can be expected to entail students working in ways that resemble sought-after scientific practices (Čančula et al., 2015). More precisely, during the prototyping typical in *engineering* activities, students can be expected to design tests for achieving self-determined goals, evaluate the outcome of their tests, and iteratively revise their constructions to accommodate those outcomes. This sequence of reasoning may constitute what Gregorcic et al. (2017) describe as the “seed[s] of scientific practices” (p. 14)—or perhaps more appropriately in the case of *Algodoo*, the seeds of engineering practices.
A responsive physics teacher can take pedagogical advantage of students’ *engineering* tasks by prompting students to reflect on their prototyping process, which may subsequently be turned into a discussion of the characteristics of scientific and engineering practices more broadly (Etkina et al., 2019, 2010). Alternatively, since *Algodoo* allows for the ‘zooming in on’ and the ‘unpacking of’ the various parts within a construction, teachers can utilize students’ constructions as the focus for further inquiry. This is another way of looking at what occurred, for example, when the participants in Paper IV lodged an arrow into the “sponge” in *Algodoo* (Section 7.1.4 above). Recall that in that case, the researchers were able to utilize the participants’ success in meeting their goal as the basis for a discussion on how non-rigid bodies are modeled in the software (and subsequently the meaning of spring damping).

**Summary and discussion of activity types**

When allowed to explore software such as *Algodoo* in a self-directed manner, students are likely to engage in some combination of the three activity types detailed above, each of which can be potentially productive for the teaching and learning of physics in their own way (Table 6, next page). A teacher who allows students to engage in this kind of activity can choose to build upon students’ exploration (Robertson et al., 2015) during any of the three activity types in order to guide the students’ attention to the type of discussion that the teacher wants. Building from the first activity type, students’ *exploration of the software fundamentals*, a teacher can encourage students to explore the meaning of various parameters as they are uncovered in the software interface. With students’ *testing and contrasting*, the second activity type, a teacher can springboard into entry-level discussions on the role of modeling in physics and the function of computer modeling in scientific inquiry. Finally, from the third activity type, students’ *engineering*, teachers can take on students’ creations for discussions around scientific practices and/or as inspiration for more topic-specific discussions of particular phenomena. Among other things, allowing students to explore less-constrained physics software such as *Algodoo* in a self-directed manner can signal to those students that their creativity, divergent thinking, and, ultimately, *agency* (Holmes et al., 2020) are valuable to the process of learning—and doing—physics.
Table 6. A summary of the three activity types identified in students’ use of Algodoo without a specific prompt.

<table>
<thead>
<tr>
<th>Activity Type</th>
<th>Explanation</th>
<th>Productiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploration of the software fundamentals</td>
<td>Students develop a sense for the tools and functions of the DLE</td>
<td>Students can naturally uncover relevant physics parameters</td>
</tr>
<tr>
<td>Testing and contrasting</td>
<td>Students explore how the DLE’s physics engine compares with the real world</td>
<td>Can serve as a backdrop for discussions about physics modeling and the use of computers in science</td>
</tr>
<tr>
<td>Engineering</td>
<td>Students create machines and pursue self-determined goals</td>
<td>Students’ engagement in science- and engineering-like practices may be unpacked for further discussion; students’ creations can be taken up as the focus for further inquiry</td>
</tr>
</tbody>
</table>

7.3 The implications of responsive teaching IV & V

Having presented the analyses of Paper IV and V, I will now reflect on the implications of the responsive teaching advocated for in this chapter as part of Theme 3. First, I review how such responsive teaching, when combined with less-constrained DLEs, has the potential to support goals other than efficient content mastery. Then, I discuss the extent to which responsive teaching stands to benefit the teachers that engage with it. Finally, in an attempt to go beyond the optimistic musings of what is typical in digital technologies work in PER, I address some of the larger barriers to implementing responsive teaching to teaching physics alongside less-constrained DLEs.

7.3.1 The benefits to students: going beyond conceptual mastery

In Chapter 3, I discussed the potential for less-constrained DLEs like Algodoo to promote certain goals that go beyond the conceptual mastery intended with constrained DLEs: among them, for students to form a more interconnected picture of physics knowledge and for students to work creatively toward solving their own lines of inquiry. In regard to the former, the case studied in Paper IV exemplifies how a pair of students can seamlessly move from a self-set goal (of puncturing a sponge, Part 1), to model construction (for a non-rigid body, Part 3), to the exploration of a specific physics parameter (spring damping in the context of a harmonic oscillator, Part 4). Much of the conventional wisdom in the design of physics DLEs would suggest that a physic educator who wants students to engage in any of these activities needs to involve three separate interactive phenomenaria-type (constrained) DLEs which each maximize student productiveness toward one of those activities. However, less-constrained DLEs like Algodoo can afford students the opportunity to explore phenomena simultaneously as part of complex systems—i.e., through the
combination of unforeseen phenomena, like projectile motion and non-rigid bodies (Part 1)—and/or sequentially as lines of ‘phenomena-hopping inquiry’—i.e., through the ‘zooming-in’ on a particular physics parameter, such as spring damping. The impact of this cross-topical capability should be investigated further to assess the degree to which it promotes students’ view of physics knowledge as interconnected. Nonetheless, especially as presented in the case study of Paper IV, less-constrained DLEs show promise for encouraging students to see physics as an interrelated body of knowledge insofar as they allow for students’ inter-topical exploration and construction of physics-relevant digital artefacts.

To the other learning goal for DLEs to promote student creativity, Papers IV and V above highlights how student creativity can be valued and built upon by responsive teachers. As I examined in Paper II (Section 5.2), software such as Algodoo is built with the intent of users actively constructing and manipulating digital objects relevant for physics learning. This is ostensibly a result of Algodoo’s implicit constructionist design philosophy (Gregorcic & Bodin, 2017), which relies on students working creatively with mathematically-rich materials. Especially in less-constrained DLEs, students have the creative leeway to bring objects together in unexpected, yet fruitful constructions. As exemplified in Paper IV by the progression of the session from Part 2 onward—and as recommended to coincide with students’ engineering activities in Paper V—teachers can take students’ unique constructions as stepping-off points for discussions and new prompts, all in a manner which explicitly signals to the students that their creativity is valuable and worthwhile. In this type of responsive teaching, wherein teachers value students’ divergent thinking and productively build on student-made models for the purposes of learning physics, students are likely to be more intrinsically motivated and may develop more ownership of the physics content itself (for a discussion of these points, see Holmes et al., 2020; Van Dusen & Otero, 2015).

7.3.2 The benefits of responsive teaching for teachers

Beyond the benefits to students, the responsive teaching arrangement that I advocate for in Paper IV and V also affords some benefits to the interested physics teacher. First, physics teachers responsively guiding students alongside less-constrained DLEs like Algodoo are provided a unique vantage point from which to form a picture of where students ‘are’ in their understanding. This can be facilitated through an attention to the involved DoVs that constitute students’ enacted relevance structures—as demonstrated in Part 1 of Section 7.1.4. Similar to the more familiar pedagogical practice of whiteboarding (Wenning, 2005), students’ involvement of DoVs in less-constrained DLEs can act as a public display of their reasoning. In my teaching experience and the teaching experience of my collaborators, this is especially useful when orchestrating feedback to several groups of students working independently.
within the same physics classroom, since you can glean insight into the progress of students within a relatively short window of attention.

Another benefit to working alongside students in the manner displayed above is that it allows the physics teacher to do the rewarding work of engaging with students’ inventiveness. The unpredictable constructions which students generate within less-constrained DLEs can function as interesting and exciting riddles for the responsive teacher to utilize in pursuit of tangentially-related physics content goals. I find that this type of improvisational work with student ingenuity is both gratifying and invigorating in our work as physics teachers, a point which should not be disregarded in the pursuit of bettering physics education overall.

7.3.3 Implementing responsive teaching IV & V

The implementation of responsive teaching alongside less-constrained DLEs comes with challenges, especially with regard to the proper training of responsive teachers (Goodhew & Robertson, 2017) and the feasibility of implementation amongst common structural barriers (e.g., high student-teacher ratios, lack of resources). While I have so far used this chapter to highlight ways in which students’ use Algodoo can be productive for the physics classroom, it is worth discussing some of these potential challenges physics teachers might face when encouraging an entire class of students to “freely explore” with less-constrained DLEs. I will highlight three examples here of some of the most pressing challenges facing implementing responsive teaching with less-constrained DLEs in a physics classroom: namely, the classroom management of divergent groups, the slower pace in meeting content goals, and the loss of a shared experience (or object of learning) for the entire class.

First, in larger classes it may be difficult to manage multiple groups of students that may be headed in divergent, often unrelated, directions. It should be pointed out that, while the data presented in this thesis involved isolated groups of students with a dedicated researcher(s) attending to their activity in isolation, I report anecdotally that the suggested role of teacher-as-responsive-guider alongside the less-constrained DLE, Algodoo, has remained tractable for myself and my collaborators in physics classes on the scale of 20-30 students per teacher (arranged in ~10 groups of 2-3 students). Alternatively, teachers facing issues in implementing Algodoo in their classes with responsive teaching can encourage students to explore Algodoo within a lab-style setting where student-teacher ratios tend to be smaller.

A second challenge that physics teachers might face when implementing responsive teaching alongside Algodoo in their classroom is that allowing students to “mess about” in less-constrained DLEs takes more time to reach certain learning goals when compared to more pointed discussions/lectures of desired topics. My recommendation regarding this concern is that teachers consider incorporating student-directed use of Algodoo into their toolbox of
active learning approaches and ultimately decide for themselves what balance to strike in the pacing of content goals.

Finally, since every student group will, by design of such a teaching approach, end up engaging in different activities and pursuing their own goals, a third challenge teachers might face when incorporating Algodoo in their classrooms is that there is a loss of a single shared experience for students. In response to this last challenge, I recommend that teachers intermittently pull the full class together for a discussion around a particular group’s work. This may help all of the students reflect on the nature of their own work and may encourage them to generalize some of their productive ideas across the various contexts that appear in other students’ work (see Tabak, 2004).

7.4 Responsive teaching alongside a less-constrained DLE IV & V

In this chapter (comprising the research published in Papers IV and V), I used the lens of variation theory and a grounded-theory-type, iterative analytic perspective to explore a teaching arrangement wherein physics teachers responsively guide students as they use less-constrained DLEs (such as Algodoo). In doing so, I was contributing in Theme 3 to answering the question,

*how can teachers effectively interpret and guide students’ use of the less-constrained digital learning environment Algodoo such that those students engage in productive activities for their learning of physics?*

In Paper IV, I demonstrated how physics teachers can effectively respond to students’ use of Algodoo in two key ways. The first of these involves a responsive teacher interpreting and valuing students’ enacted relevance structures through an attention to the DoVs involved by those students within Algodoo. The second responsive technique involves (1) recognizing a DoV worth focusing on during students’ use of a Algodoo, (2) guiding students to construct their own systems and models that provide access to that DoV (i.e., such that the model is uncomplicated enough that the significance of the desired DoV can be discerned within the context), and then (3) encouraging the students to vary the DoV (adapted from Fredlund, Airey, et al., 2015). In Paper V, I utilized a grounded-theory-type perspective to iteratively code participants’ use of Algodoo across multiple case studies. This analysis resulted in the identification of three activity types that are likely to feature during physics students’ exploration of Algodoo: (1) exploration of the software fundamentals, (2) testing and contrasting, and (3) engineering. I discussed how a responsive teacher can leverage each of these activity types as the foundation for a productive physics discussion.
When compared with the predominant practice of using constrained DLEs in physics teaching, the teaching arrangement featured in this chapter allows students to transition fluidly between physics topics and has the potential to better promote students’ creativity during physics learning. This may help physics students appreciate the interconnectedness of physics knowledge and provides physics teachers with better means for valuing and building upon students’ divergent thinking. Furthermore, regardless of whether students are ‘poking around’ in *Algodoo*’s menus, checking the boundaries of the software’s physics engine, or creating machines to meet their own goals, physics teachers can be assured that the time spent by students exploring less-constrained DLEs is a near neighbor of a worthwhile physics discussion. Thus, as long as the interested physics teacher is willing to build upon the divergent activity of students, they can ensure that their students are never ‘far from the shore’ of productive physics discussions.

A reasonable point could be raised that the arrangement of responsive teaching alongside a less-constrained DLE does not depart from a constraints-based pedagogical philosophy so much as it merely shifts the burden of constraints from within the DLE to the teacher. While this may be the case to an extent, I would like to emphasize that the constraints imposed by a responsive teacher alongside a DLE are not only more flexible in nature, but likely also fewer in number than the constraints employed within most constrained DLEs (c.f., the comparison of decisions cued/given to students in traditional and non-traditional labs, Holmes et al., 2020). This is reflected in the student-centeredness of responsive teaching, which calls for the foregrounding of students’ ideas and the utilization of them as starting points for educational activity—neither of which ideals are as supported in constrained DLEs. Instead, with less-constrained DLEs, students can be provided with opportunities to try out more of their own ideas, even the disciplinarily-incorrect ones. This is because such learning environments allow for a wider range of phenomena to be explored and for a larger diversity of DoVs to be incorporated.

Methodologically, this chapter (especially Paper IV) also illustrates how the analytic perspective of variation theory lends itself particularly well to the study of physics students’ use of DLEs. The DLEs used in the teaching and learning of physics comprise collections of physics DoVs to be discerned. In constrained DLEs, the DoVs are chosen sparingly in order to encourage specific lines of inquiry and particular conceptual mastery. In less-constrained DLEs, a wider range of DoVs are compiled in order to allow students’ divergent inquiry and creativity with physics-relevant materials. While I have focused on the latter type of DLE in my doctoral work, the variation-theory-informed perspective I have developed arms the interested physics education researcher and physics teacher with a means for gaining insight into what students see as relevant in any physics DLE. Furthermore, this chapter provides physics educators with explicit recommendations for how to guide students toward the discernment of new physics parameters within DLEs, especially

204
where the structure of the DLE provides students with sufficiently-creative space to do so. In this way, I further nuance discussions around the structure of the digital tools used in the teaching and learning of physics and contribute to the development of best practices in their use by physics educators.
8 Synthesis of findings

In the previous three chapters, I presented the data and analyses from the five papers that constitute the peer-reviewed work of this thesis (as organized into three themes). In this chapter, I discuss how my results can be synthesized across the five papers to provide meaningful insights into physics students’ use of DLEs during small-group work. To do so, in Section 8.1 I first summarize my answers to the three research questions posed in Chapter 1. Then, I reflect on the ‘ecosystem’ of digitally-rich physics meaning-making on which my thesis work has centered in Section 8.2. Finally, in Section 8.3 I return to theoretical framing of flexible facet profiles detailed in Chapter 3—as based on Perkins’ (1991) taxonomy for learning environments—and take this framing to fruition in light of the results from my five papers.

8.1 Answering my research questions

**Research Question 1**

*As a concrete example of a less-constrained digital learning environment, how can Algodoo be observed to act as a mediator for students between the ‘physical world’ and the ‘formal world’ of physics?*

In Paper I, I combined the perspectives of semi-formalisms (diSessa, 1988) and modeling (Hestenes, 1992) and found that a pair of participants made multimodal meanings through their movement between the physical domain, the formal domain, and the semi-formal domain of Algodoo. For example, the participants answered a question about their digital model in Algodoo by pointing to a distance in the physical ramp setup. Analytically, by tracking the moment-to-moment meaning-making of the participants in the form of talk and environmentally-coupled gestures, I was able to observe the instances where the participants were articulating their reasoning across domains. This composite perspective of semi-formal modeling could be utilized to reveal the extent to which a DLE like Algodoo mediates between the ‘physical world’ and ‘formal world’ of physics.

In Paper II, again through an attention to participants’ moment-to-moment meaning making around the DLE Algodoo, I observed how the mathematical
materials within the software were recruited by participants in physically-intuitive ways. I was able to see how the structure of Algodoo observably connected participants to the formalisms of physics by making them more physically intuitive. The software allowed mathematically-rich representations to be presented to the participants as something around which they could safely and inventively build intuitive understandings. Thus, my analysis in Paper II showed another way that DLEs like Algodoo might functionally ‘mediate’ between physical and formal worlds.

I then combined the findings of Paper I and II in order to define a semi-formality ‘criterion’ for DLEs (especially Controllable Worlds). I use the term semi-formality to refer to the degree to which a DLE functionally mediates between the physical and formal worlds of physics by providing a physically-intuitive space within which students can create with the formal materials of the discipline of physics.

**Research Question 2**

*How can students working in a digitally-rich environment be observed to make use of embodied, non-disciplinary meaning-making resources to reason in ways that are continuous with disciplinary-relevant aspects of a given physics task?*

In Paper III, I combined the perspectives of social semiotics/conversation analysis and embodied cognition into a single multi-perspective analytic model. This was done for the purposes of analyzing an embodied dance in which the participants Adam and Beth engaged during a task on orbital motion. I interpreted the pairs’ (largely non-disciplinary) semiotic resources as implying embodied imagery, which were then evaluated against a set of four disciplinary-relevant aspects (DRAs) for a question involving the orbital periods of stars in a binary star system. In doing so, I was able to explore the extent to which that Adam and Beth’s non-disciplinary meaning-making resources such as gesture, haptic-touch, body position, and talk were coordinated in ways that were continuous with disciplinary physics. The results of Paper III expanded the theoretical picture of coordinating hubs from social semiotics (cf., Fredlund et al., 2012; Volkwyn et al., 2018), further nuanced the (perhaps misleading) distinction between kinesthetic and embodied learning activities, and depicted a multimodally-rich example of fruitful embodiment in terms of an enacted metaphor for the topic of orbital physics.

**Research Question 3**

*How can teachers effectively interpret and guide students’ use of the less-constrained digital learning environment Algodoo such that those students engage in productive activities for their learning of physics?*
In Paper IV, I attended to participants’ moment-to-moment interactions through the perspective of variation theory (Marton & Booth, 1997) and developed practical recommendations for how physics teachers can effectively respond to students’ use of less-constrained DLEs like Algodoo. First, I illustrated how teachers can attend to the dimensions of variation (DoVs) that students involve during their use of the DLE so as to form a picture of the students’ enacted relevance structures. Then, through an example where a pair of participants demonstrated a lack of confidence in the DoV of damping, I discussed how a physics teacher can responsively guide students toward learning about new physics parameters (i.e., open up new DoVs) within less-constrained DLEs by leading students toward building simple models that make the contrast of that parameter more directly experienceable.

In Paper V, I utilized a grounded-theory-type perspective to identify three activity types in which physics students are likely to engage during exploration of Algodoo: (1) exploration of the software fundamentals, (2) testing and contrasting, and (3) engineering. With each of these three activity types, I presented examples of how a responsive teacher can springboard into productive physics discussions with students.

Taken together, the findings from Papers IV and V show how the teaching arrangement of responsive teaching alongside less-constrained DLEs like Algodoo may help physics students appreciate the interconnectedness of physics knowledge and provides physics teachers with better means for valuing and building upon students’ divergent thinking. Moreover, physics teachers can be assured that the time spent by students exploring less-constrained DLEs like Algodoo is very often a ‘near neighbor’ to a worthwhile physics discussion.

8.2 Looking across the five papers

As I suggested in Chapter 1, the work of this thesis can be conceptualized as my exploration of an ‘ecosystem’ of digitally-rich physics meaning-making. More precisely, each of the papers of this thesis have in one way or another explored the relationships between a Controllable World (to reiterate, those digital (educational) technologies that provide users with control over a manipulable virtual environment), a small group of participants (acting as students), the physical world, and a set of researchers (acting as teachers) (see Figure 44).

In Paper I, I explored how a pair of participants navigated between the software Algodoo and the physical setup of a ramp and puck—thereby exploring the theoretical relationship between students, the physical world, and a Controllable World, in the ‘ecosystem’ of this thesis. In doing so, I developed a methodological perspective for tracking how physics students can be observed to move between software such as Algodoo and the physical world.
through their multimodal interactions. Through my analysis of the participants’ video-recorded interaction, the Algodoo Controllable World was seen to be the locus of semi-formal modeling. I thus also demonstrated how physics students’ modeling might be noticed (by teachers or researchers, alike) through an attention to the details of students’ moment-to-moment communication and interaction with and around a Controllable World.

In Paper II, I explored how participants navigated between the formal mathematical representations within Algodoo via their physical intuitions—thus again, in the ‘ecosystem of this thesis, exploring the theoretical relationship between students as experiencers of the physical world and a Controllable World. To do this, I employed the concepts of constructionism to show how students might make use of the mathematical materials within Controllable Worlds like Algodoo to intuitively make sense of physics phenomena. My analysis of participants’ gestural activity around the IWB in combination with their talk revealed how mathematical representations can be used by students in unconventional, yet meaningful ways. In the context of this thesis, the findings of Paper II were combined with those of Paper I, comprising the theme of ‘Bridging the physical and formal’ (Theme 1).

In Paper III, I analyzed the embodied interactions of a pair of participants against the backdrop of My Solar System running on an IWB—thereby exploring the theoretical relationship between students in the ‘ecosystem’ of this thesis. I combined the perspectives of social semiotics and embodied cognition in order to interpret the informal, embodied interaction of participants as they reasoned about a physics phenomenon. Using this new methodological
and theoretical framing, I produced a nuanced description of how physics students can incorporate their bodies while engaging in mechanistic reasoning, especially in a digitally-rich learning environment. The findings of this work comprise the theme, ‘Embodiment and the making of meaning’ (Theme 2).

In Paper IV, I explored how researchers productively responded to a pair participants’ use of the less-constrained Controllable World, Algodoo—thus, exploring the theoretical relationship between teachers, students, and a Controllable World, in the ‘ecosystem’ of this thesis. I employed the lens of variation theory to illustrate via case study how physics teachers might both interpret students’ enacted relevance structures, and also guide students toward the learning of specific physics parameters by leading those students toward building simple models that make the contrast of those parameters more directly experienceable. I argued that encouraging physics students to utilize less-constrained Controllable Worlds in this way has the potential to increase the perceived interconnectivity of physics knowledge and, through the valuing and building upon of students’ divergent ideas, the potential to foster learning environments wherein students are more agentive.

In Paper V, I identified patterns in participants’ self-directed use of Algodoo and suggested ways that those patterns could be leveraged by physics teachers—thus, further exploring the theoretical relationship between teachers, students, and a Controllable World, in the ‘ecosystem’ of this thesis. A grounded-theory-type method was used to code seven pairs of participants’ free exploration of the Controllable World into three activity types: namely, exploration of the software fundamentals, testing and contrasting, and engineering. I discussed how a responsive physics teacher could springboard from each of the three activity types into a productive discussion for the physics classroom. Taken within the context of this thesis, I combined the findings of Paper V with those of Paper IV in a theme around the ‘Responsive role of the physics teacher’ (Theme 3).

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 through the use of Controllable Worlds (organized into three thematic explorations of a relational ‘ecosystem’). Especially as compared to the types of PER projects which might conduct pre- and post-testing 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 the Controllable Worlds Algodoo and My Solar System can lead to student behavior which is productive for physics teaching learning in ways that may be altogether unexpected.
8.3 On Controllable Worlds and flexible facet profiles

In Chapter 3, I detailed a taxonomy based on Perkins’ (1991) work, which posits that learning environments are generally made up of six facets: information banks, symbol pads, construction kits, phenomenaria, task managers, and interactional spaces—the last facet of which I added for the purposes of better attending to the collaborative aspect of my CSCL-aligned research. Each learning environment displays some combination of these facets—as constituted by actors and artefacts embedded in social arrangements—in what is termed a facet profile. Importantly, the facet profile of a learning environment carries with it implicit (sometimes explicit) premises about what learning and teaching a subject should entail. Within this theoretical frame, digital learning environments (DLEs) can be seen as self-contained digital arenas that fulfil some subset of the facets within a learning environment. However, the subset of facets that a DLE takes on is context dependent—contingent both on the material setting within which the DLE is situated and also on the particular students/users making use of the DLE. In this way, my framing of facet profiles relates to the notion of variable affordances (e.g., Borghi & Riggio, 2015) whereby the functional significance of an object (or software) is not fixed by the designer but rather negotiated during use with respect to the context. I contend, following from the implications of the taxonomy of flexible facet profiles I proposed in Chapter 3, that it is more productive for physics education researchers such as myself to discuss the range of possible facet profiles that physics DLEs observably take on rather than attempting to establish a single facet profile for any given DLE. Furthermore, I argue that it is practically useful, then, to attend to the broader contextual factors that may shift a physics DLE’s facet profile and the potential pedagogical motivations for physics educators to pursue specific facet profiles for the DLEs incorporated into the learning environments they oversee.

In this final section of Chapter 8, I would like to take this theoretical framing of flexible facet profiles to fruition. Having paid particular analytic attention in this thesis to participants’ use of Controllable Worlds—the particular class of DLEs that provide users with control over a manipulable virtual environment—I can now flesh out what I see to be a logical implication of the facet profile view specifically for Controllable Worlds. This comes in the form of a two-dimensional facet profile ‘space’ for Controllable Worlds (including some programming environments, for reasons I will explain below) based on the two continua of constraints and semi-formality—two continua that I have developed in the course of writing this thesis (see Chapter 3).

For the purposes of my discussion of DLEs here, I have decided to include programming environments within the ‘space’ of Controllable Worlds—despite the two being distinct topical areas of digital technologies work within PER (Section 2.3). My reasoning for including programming environments
alongside Controllable Worlds software such as *Algodo* and PhET simulations in this section stems from the fact that programming environments can, and often are, used by physics students to create their own manipulable virtual environments that functionally resemble Controllable Worlds (e.g., the programming tasks given to students in Svensson et al., 2020). The programming environments that can be observed to function as such *result* in Controllable Worlds through the running of editable code. It is for this specific implementation of programming environments (not programming environments in general) that I include them within the Controllable Worlds space outlined below.

The meaningful difference between this kind of implementation of programming environments and ‘pre-packaged’ Controllable Worlds such as *Algodo* is that, when physics students generate their own virtual worlds by directly engaging with the coding language of a programming environment, they are able to edit the architecture of the resulting Controllable World to a greater extent. This capability for basal editability requires that the programming environments be what diSessa (2016) described as ‘generic media.’ By this, he meant the building blocks of the media (i.e., the callable commands of the coding language) are non-specific in their situational application. As I have already suggested in Chapters 3 and 5, this non-specificity comes at the cost of the programming environments being non-intuitively matched to the virtual environments they might produce. As diSessa describes,

>[…] generic media have a critical shortcoming. The distance to specific application may sometimes be too large to suffer. There may be what some call the “Turing Tarpit,” where everything is possible, but nothing is easy. A more apt description is that some things may be easy, but few of them are exactly what you want to do.

(diSessa, 2016, p. 67)

The characteristic of a DLE being physically intuitive to manipulate for the phenomena at hand relates to what I described in this thesis as *semi-formality*. As such, the programming environments I include in this section that result in ‘Controllable Worlds’ may functionally resemble the (less-editable) Controllable Worlds of *Algodo* and PhET simulations to an extent, but necessarily have a lower degree of semi-formality.

8.3.1 Defining the ‘space’ of Controllable Worlds

In Section 3.3, I argued for the notion that Controllable Worlds that function as *construction kits* could be differentiated from Controllable Worlds that function as *phenomenaria* based on the criterion of *constraints*. Using the notion of ‘dimensions of variation’ (DoVs) from Paper IV, the constraints criterion refers to the degree to which the set of DoVs made available by the software is restricted. Designers of *phenomenaria*-functioning Controllable
Worlds, which in PER are typically referred to as simulations, tend to intentionally limit the set of DoVs to only those readily applicable to a specific phenomenon (see Section 3.3). Conversely, designers of construction-kit-functioning Controllable Worlds, which in physics are sometimes referred to as microworlds\(^{51}\) or programming environments, tend to provide a wider array of DoVs that do not necessarily pertain to any one phenomenon. Thus, through an attention to the range of DoVs made directly available through a Controllable World (and/or as a result of the broader contextual factors), one can differentiate between Controllable Worlds by the degree to which they are constrained (Figure 45).

![Figure 45. The constraints continuum for Controllable Worlds.](image)

In Section 5.3, after having presented how Algodoo can be seen to function as a mediator between the physical domain (in terms of a physical setup as well as the physical intuitions of the participants) and formal domains, I posited that the criterion of ‘semi-formality’ can be used in a similar manner to constraints to differentiate between the functions of Controllable Worlds. To reiterate, a Controllable World’s semi-formality is the degree to which that software provides a physically-intuitive space within which students can create with the formal materials of the discipline of physics. It should be noted that there is a liability for confusion in my use of the term ‘semi-formality’ as a criterion in this way: a phrase such as ‘more semi-formal’ could ambiguously be interpreted as meaning either more of the formal mathematics or more of the physical intuitiveness. I entreat the reader to remember that I am referring to the latter when using the semi-formality criterion.

The criterion of semi-formality can be used to differentiate between what I will now call ‘microworlds’ and programming environments that are used to create manipulable environments (both of which are generally less-constrained, construction-kit-functioning Controllable Worlds). Algodoo provides access to the mathematical materials of physics through the physically-intuitive means of two-dimensional shape manipulation, while most programming environments typically require users to summon the mathematical materials of physics through abstracted lines of code. Thus, Algodoo can be said to have a higher degree of semi-formality than is typical of programming environments. An analogous continuum to Figure 45 for constraints (above) can be made for differentiating between Controllable Worlds with a higher or lower degree of semi-formality (Figure 46, next page). The My Solar System

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\(^{51}\) My suggestion for the ambiguity of the ‘microworld’ label is taken up below.
PhET simulation utilized by participants in Paper III also has a relatively high degree of semi-formality—physical familiarity and intuitive controls are stated as core tenants of the PhET design principles (W. Adams et al., 2006)—so it can be placed toward the same end of the semi-formality continuum as Algodoo. The next logical step is to combine the two continua of constraints and semi-formality described above into a two-dimensional space for the possible Controllable Worlds in physics education (Figure 47).

Within this space, *construction-kit*-functioning Controllable Worlds would be placed on the left side and *phenomenaria*-functioning Controllable Worlds on the right. ‘Physically intuitive’ Controllable Worlds (i.e., those Controllable Worlds with a high degree of semi-formality) would be placed in the upper half and ‘physically non-intuitive’ Controllable Worlds in the lower half.

### 8.3.2 The quadrants of the Controllable Worlds space and moving between them

Having now posited the Controllable Worlds space, it is worthwhile for me to discuss the pedagogical consequences that Controllable Worlds in each of the four quadrants entail for the physics students that use them. In terms of the
past and present PER work on digital technologies, the most readily-explored quadrants of this space are the upper right and bottom left.

In the upper right quadrant, Controllable Worlds function as constrained and with a high degree of semi-formality. This is where the productively-constrained simulations discussed in Section 3.3 would generally be found. Beyond being constrained, however, these Controllable Worlds are semi-formal as well: that is, they allow students to interact with virtual spaces that resemble the physical world and employ physically-intuitive controls such as sliders and buttons (W. Adams, Reid, et al., 2008a). The constrained nature of these Controllable Worlds tends to efficiently and reliably focus students’ attention on the relevant aspects of phenomena (recall my discussion of the prevailing philosophy for DLEs in PER, Section 3.3), while high degree of semi-formality of these Controllable Worlds allows students to explore and manipulate these environments in terms of their physical intuitions (recall the discussion of semi-formalisms in 5.1.1). To generalize from this, one can surmise that the educational benefits to Controllable Worlds functioning in the upper right quadrant include that the physics students utilizing them are generally more likely to learn specific conceptual material through physically intuitive means, all without a significant time investment into learning how to use the software themselves (see Figure 49 on the next page).

In the lower left quadrant of the Controllable Worlds space, the Controllable Worlds function as less-constrained and with a low degree of semi-formality. This is where physics programming environments would generally be found. The less-constrained nature of programming environments that produce Controllable Worlds tends to result in students having the leeway to engage in the systematic and selective decision-making required in physics modeling, even when the mathematics involved might be otherwise ‘out-of-reach’ (MacDonald et al., 1988; Redish & Wilson, 1993; Wilson & Redish, 1989). Furthermore, the lower degree of semi-formality in programming environments that produce Controllable Worlds tends to allow physics students to engage with a skillset typical of the “professional physicists” (i.e., computational reasoning and, more overtly, coding itself) and to begin to deal with “more realistic problems” (requiring numerical methods, for instance) that otherwise have to be tidied up or ignored with other physics teaching approaches (Redish & Wilson, 1993, p. 228). Thus, to generalize again, one can surmise that the educational benefits of Controllable Worlds functioning in the lower left quadrant are that the physics students utilizing them are generally able to deal with mathematically-rich processes of modeling and the
‘untidied’ complexities of real physics phenomena, all while developing a skillset that is used by physics disciplinary insiders (Figure 48). 52

The research in this thesis has generally been focused on Controllable Worlds that function in the upper half of the Controllable Worlds space: that is, those Controllable Worlds that—by virtue of the software design and the broader contextual factors of an IWB and open-ended prompts, for example—were used by participants in a manner consistent with a high degree of semi-formality (intuitiveness). However, through my examination of participants’ use of Algodoo in Papers I, II, IV and V, I have especially contributed to a better scholarly understanding of digital tools that may function in the heretofore under-researched upper left quadrant of the Controllable Worlds space. I contend that this upper left quadrant is where so-called microworlds would generally be found.

As an aside, I am understandably reticent to employ the label of microworld to the upper left quadrant of the Controllable Worlds space given the wealth of controversy that has surrounded the term and its frequent overapplication to practically every type of Controllable World at some point by some researcher(s). Nonetheless, in light of the work presented in this thesis I argue that I am now positioned to provide a more specific (if more complicated) definition for microworlds that renders the term useful anew for PER: for the purposes of physics education, **microworlds** are Controllable Worlds that function as less-constrained and with a high degree of semi-formality.

52 Employing the social semiotic perspective of Airey and Linder (2017) here, I would interpret this latter point—that programming DLEs involve a skillset that is actually used in the discipline of physics—would be expressed as programming DLEs having higher ‘disciplinary affordance.’
It follows from combining the educational benefits of functioning with a high degree of semi-formality (as I have discussed for simulations) with the benefits of being less-constrained (as I have discussed for programming environments), that one would theoretically expect to see that Controllable Worlds that function with both a high degree of semi-formality and also as less-constrained would allow students to use their physical intuitions to engage in the physics modeling process and otherwise ‘messy’ aspects to physics problem-solving. This is precisely what I have found in the research of this thesis involving participants’ use of Algodoo. The research of this thesis suggests that the educational benefits of microworld-functioning Controllable Worlds include that physics students are able to intuitively engage in mathematically-rich modeling and creatively divergent problem-solving, all with relatively little time investment into learning the DLEs themselves (see Figure 49).

![Figure 49. The upper left and lower right quadrants of the Controllable Worlds space.](image)

Now for completeness’ sake, I turn to the fourth and final quadrant of the Controllable Worlds space, within which Controllable Worlds function as constrained and with a low degree of semi-formality. To the best of my knowledge, the software that would reside in this quadrant are relatively uncommon in physics education and, thus, also relatively unexplored in the PER community. The constrained nature of Controllable Worlds in this quadrant would tend to imply that students would learn specific physics content more efficiently and reliably. The low degree of semi-formality of Controllable Worlds in this quadrant would tend to imply that students would engage in phenomenon-specific computational practices that resemble those used in the physics discipline. An example of a kind of Controllable Worlds that would
reside in the lower right quadrant of this space may be the runnable ‘simulated experiments’ implemented by early computer advocates of the 1960s in physics education:

A promising computer application is simulation of experiments. A given experimental situation is represented by an equation or set of equations programmed into the computer. After the student specifies a set of initial conditions, the computer generates data such as those the student would gather in an actual experiment. The student does not have direct access to the simulation program itself, and his objective is usually to determine these relationships from the data, just as in a real experiment, by curve plotting and data analysis. The simulation program can be written so that the data generated by the computer include uncertainties corresponding to experimental error. Also, values of parameters can be varied from one presentation of the problem to the next by generation of random numbers within a given numerical range.

(Schwarz et al., 1969, p. 42)

As Schwarz et al. (1969) point out, students using these types of ‘simulated experiments’ can be compelled to work with important aspects of physics involving uncertainty and data analysis. Still, as I mentioned above, these types of simulations—which I choose to call ‘black box’ simulations—where students have little to no interactivity with the Controllable World beyond setting the initial conditions, are uncommon among the digital technologies of PER. Typically, if a piece of Controllable World software is designed today to provide students with access to the details of a phenomenon (i.e., highly constrained), the designers tend to opt for high levels of interactivity and intuitive control as well (i.e., the higher degree of semi-formality seen with the common PhET-style simulations). Nonetheless, I can speculate on the educational benefits of Controllable Worlds functioning in the lower right quadrant of the Controllable Worlds space to presumably include that physics students are able to engage in some disciplinary-authentic practices used by physicists while efficiently learning specific content knowledge (Figure 50).

With the ‘character’ of each quadrant now laid out, it is important to recall that in keeping with the notion of flexible facet profiles for DLEs, the position of a Controllable World within this theoretical two-dimensional space is context dependent. In fact, among other things this thesis presents some examples of the broader contextual factors that physics educators can wield in shifting Controllable Worlds around within the two-dimensional space described above. For example, I interpret the IWB interface used by participants in Papers I-IV as having the effect of increasing the functional semi-formality of the respective Controllable Worlds accessed through it. In Paper III, the participants engaged in highly-embodied interactions alongside the My Solar System PhET simulation and I argue that the IWB predisposed the interactional space facet around the DLE such that the participants were encouraged to do so (Section 6.2). In this way, the use of an IWB so far appears to have the
effect ‘moving’ the function of a DLE vertically upwards in the Controllable Worlds space.

Likewise, the responsive guidance of a physics teacher can functionally shift a Controllable Worlds rightward in the space. In Paper IV, participants were led by the responsive researchers from the generally less-constrained environment of *Algodoo* paired with an open-ended prompt, to a phenomenon-specific exploration of spring damping in an oscillator (Section 7.1.4). Thus, through responsive teaching techniques, the researchers in that case effectively shifted the function of *Algodoo* away from a general *construction kit* function toward a more constrained *phenomenarium* function for the purposes of specific content learning. However, there is an apparent asymmetry around the role of responsive feedback in the space of Controllable Worlds: though less-constrained Controllable Worlds can be functionally shifted to be more constrained (rightward in the space)—through thoughtful and pointed teacher feedback, for example—the phenomenon specificity of purpose-built, constrained Controllable Worlds makes the opposite, leftward functional shift from constrained to less-constrained more difficult to imagine. This is not to say that constrained Controllable Worlds are absolutely ‘fixed’ in right half of the space, but rather that more research is needed to determine the broader contextual factors, if any, that would functionally shift those DLEs leftward. As it stands, Controllable Worlds that are designed to be less-constrained (i.e., intended to function as *construction kits*) ostensibly have a greater capacity for horizontal ‘movement’ within the Controllable Worlds space than Controllable Worlds designed to be more constrained (i.e., intended to function as *phenomenaria*) may lack. This horizontal flexibility results in what I discussed earlier as the set of unique benefits with less-constrained Controllable Worlds (Section 7.3.1): less-constrained software like *Algodoo* can afford students the opportunity to explore phenomena simultaneously as part of complex systems—i.e., through the combination of unforeseen phenomena—and/or sequentially as lines of phenomena-hopping inquiry—i.e., through the ‘zooming-in’ on a particular physics parameter. For other less-constrained Controllable Worlds resulting from programming environments like *GeoGebra* (Lingefjärd & Ghosh, 2016; Solvang & Haglund, 2019; Walsh, 2017), it seems similarly possible to move the Controllable Worlds rightward (and/or upward and right) within the space via the coding of phenomenon-specific, manipulable environments.

Ultimately, the entire space of possible Controllable Worlds and the facet profiles on which it is predicated calls for further work in PER. The research in this thesis has contributed significantly to the understanding of Controllable Worlds in physics education, not only in the generation of a set of vocabulary for articulating the characteristics and function of these software, but also in the presentation of a body of research that begins to explore how students make use of these software in the activity of physics teaching and learning. Nonetheless, significant future research is required to further map the terrain
spanned by the Controllable Worlds space and, indeed, to test the robustness/practical utility of some of the framings set forth in this section. I deal with some other potentialities for future work in this area, at least as I see them, in Chapter 10.
9 Contributions and implications

In the preceding chapter, I discussed the findings and results of this thesis both in terms my exploration of a relational ‘ecosystem’ as well as in terms of a taxonomical space for Controllable Worlds. In this chapter, I provide a bulleted summary of the ways in which this thesis contributes to PER—both theoretically and methodologically—as well as a list of the implications of this thesis for the teaching and learning of physics.

9.1 Theoretical contributions

In contribution to theories pertinent to PER, this thesis
- presents a critical review of existing PER work related to digital technologies organized in terms of three ‘paradigms’ and seven topical areas;
- demonstrates the feasibility of multi-perspective approach to research on physics students’ use of DLEs;
- builds upon Perkins’ (1991) taxonomy of learning environments to form a theoretical perspective of flexible facet profiles for DLEs within broader learning environment contexts;
- defines a two-dimensional space for discussing the function of Controllable Worlds, as based on the continua of constraints—for differentiating between construction-kit-functioning DLEs (i.e., microworlds and programming environments) and phenomenaria-functioning DLEs (i.e., simulations and interactive visualizations)—and semi-formality—for differentiating between DLEs within the construction-kit-functioning and phenomenaria-functioning categories;
- using the two-dimensional space for Controllable Worlds, suggests potential considerations for selecting DLEs and the learning environments that surround them for specific desired facet profiles in physics education;
- provides an example of participants observably making use of a DLE in a manner consistent with that of diSessa’s (1988) proposed notion of semi-formalisms;
- meaningfully combines diSessa’s (1988) notion of semi-formalisms with Hestenes’ (1992) modeling perspective to propose a notion of semi-formal modeling in physics students’ use of DLEs;
• operationalizes the ways in which DLEs such as Algodoo can be observed to function as physics microworlds (i.e., semi-formal and less-constrained) for students as they playfully explore in open-ended tasks;
• demonstrates the viability of semi-formal, less-constrained DLEs such as Algodoo when dealing with certain topics of physics at the upper-secondary and/or introductory university levels;
• meaningfully combines the theories of social semiotics (Airey & Linder, 2017) and embodied cognition (Lakoff & Johnson, 1980) into a new ‘Knowledge in Pieces’ 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 (KLAs) and embodied learning activities (ELAs) 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;
• applies the variation theory of learning (Marton & Booth, 1997) as a lens for interpreting physics students use of DLEs and, more specifically, for responsively guiding physics students use of DLEs when those DLEs are less-constrained;
• expands variation theory by introducing the notions of involved DoVs and an enacted relevance structure and demonstrates the utility of these notions in the context of less-constrained DLEs like Algodoo;

9.2 Contributions to PER methods
In terms of methods, this thesis
• demonstrates how conversation-analytic methods can be meaningfully applied to study the physics students’ interactions, especially for the moment-to-moment use of DLEs;
• provides four examples (Papers I-IV) 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 expressed via semiotic systems other than 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 physics context deemed relevant by the discipline of physics;

• provides an example of how physics students’ exploration of less-constrained DLEs can be interpreted in terms of involved DoVs and enacted relevance structures;

9.3 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 DLEs situated in semi-isolated learning environments with open-ended prompts, such that these types of creative activities might be implemented in physics or astronomy courses;

• explains the manner in which less-constrained DLEs 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 (e.g., with large touchscreen interfaces and creative software) and epistemologically (e.g., with open-ended prompts) such that the facet profiles of the learning environment and the DLEs within it are functionally altered;

• 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;

• provides teachers with a perspective based on variation theory for the interpretation and guidance of physics students’ use of DLEs;

• depicts three patterns in participants’ use of the DLE Algodoo and proposes various productive physics discussions physics teachers can marshal in response to those patterns;
10 Future work

The text preceding this final chapter represents my forays toward a better understanding of the digital tools that are utilized in physics education, particularly *Controllable Worlds*. In presenting my work in this area thus far, I hope it has become evident to the reader that there stands a wealth of related work that could be pursued in the future by physics education researchers, physics teachers, and even the developers of digital technologies. In this final chapter of my thesis, I present some potential future projects that could stem from the work of this thesis. I also provide some frontiers of focus for the PER work relating to digital technologies: namely, potential research on the uptake of digital technologies in physics classrooms and the possibility of adaptable constraints within *Controllable Worlds*.

Future directions stemming from my work

**Building on the work of Theme 1**

As I mentioned in Section 5.2.4, one potential route for future research that would build on the theoretical notion of semi-formalisms from Paper I is to test the hypothesis that DLEs which are expected to be highly semi-formal would facilitate physics students’ conceptual connection-making between the physical world and the formalisms used in the discipline of physics. Effort aimed at this hypothesis could implemented qualitatively, in a manner similar to the methodology of Paper I, or more quantitatively through the large-N comparison of multiple digital learning environments with ostensibly different degrees of semi-formality (i.e., *Algodoop* vs. a programming environment).

Another interesting way to build upon the work of Theme 1 would be to theorize the extent to which non-digital learning artefacts can function as semi-formalisms in physics learning. It stands to reason that many of the activities already implemented in many physics learning environments aim in some ways to make the formalisms of physics into somehow physically-intuitive contexts. Perhaps then, a family of highly semi-formal artefacts can be identified such that the interested physics educator might select from a variety of semi-formal toolkit befitting the demands of their specific context.
Building on the work of Theme 2

The theoretical perspective developed in Theme 2 of this thesis could be applied to a wide range of learning contexts, especially those where embodiment is expected or encouraged. I would be interested to see, for example, comparisons of ‘summary diagrams’ (resembling Figure 32) between different student groups within the same class or between cohorts of students engaged in different activities aimed at the same physics topic.

Another future project might further examine the extent to which the interface of the digital technology affects the amount of embodied interaction that takes place during student group work. A research effort such as this could also represent one of the many potential forays into examining the impacts of contextual factors on the facet profiles of DLEs (as suggested in Chapters 3 and 8). In the case of the digital interface like an IWB, for example, how does this observably affect the interactional space facet of the DLE running on it? How are other facets of a learning environment such as task managers affected through the selection of digital interface as well? In exploring the Controllable Worlds space posited in Chapter 8, what are other contextual factors besides IWBs and responsive teaching that can ‘move’ a DLE around that space?

Building on the work of Theme 3

An interesting thread to pull related to the work done in Theme 3 of this thesis would be to examine if students’ use of less-constrained DLEs results in their viewing physics as a field of interconnected facts. Beyond this, it would interesting to challenge the assumption that the combination of a less-constrained DLE + responsive teacher results in fewer overall constraints in place than is typical with productively-constrained DLEs such as simulations—similar to the surprising work that as has been done in revealing the level of scaffolding actually inherent to ‘unstructured’ labs as compared to (more traditional) structured ones (Holmes et al., 2020).

In adapting the variation theory perspective developed in Paper IV, future research could examine the effectiveness of including a slider within a DLE—designed for the purposeful variation of a specific parameter against a fixed background—for drawing students’ attention to a physics parameter. Furthermore, this work could analyze if the presence of said slider would increase the likelihood of those students ‘learning about’ the parameter in question during use of the DLE.

Frontiers of focus for the digital technologies work of PER

Technology uptake

As I outlined in Section 2.4, the digital technologies work of PER has an apparent bias toward the design of new technologies rather than the study of how existing technologies might be best implemented. Among other things, this
leaves PER with a lack of work that studies technologies as situated within contexts and likely contributes to a fatigue of technological overpromise within the community of physics educators and physics education researchers. However, even if the digital technologies work of PER were to successfully address these issues related to innovation bias and began producing a more nuanced literature base around the implementation of existing educational technology, there would still be a lingering technological issue facing the physics education community: even the best recommendations for how to use technology from the PER field fail to ensure uptake of those technologies by actual physics teachers.

Indeed, the community of physics education researchers has a track record of issuing recommendations for the best-supported teaching practices without those recommendations necessarily translating into physics classrooms. The uptake of educational technology is a pronounced example of this,

Teachers have been infrequent and limited users of the new technologies for classroom instruction. If anything, in the midst of the swift spread of computers and the Internet to all facets of American life, “e-learning” in public schools has turned out to be word processing and Internet searches. As important supplements as these have become to many teachers’ repertoires, they are far from the [...] teaching and learning that some techno-promoters have sought. Teachers at all levels of schooling have used the new technology basically to continue what they have always done: communicate with parents and administrators, prepare syllabi and lectures, record grades, assign research papers.

(Cuban, 2001, p. 179)

At the time of writing, the COVID-19 pandemic has forced most physics teachers into uncharacteristically technological teaching arrangements. However, little is yet known about which technologies are being used and how they are being implemented. Furthermore, it remains to be seen how many teachers will continue to use the digital tools they have begrudgingly accepted once the pandemic has eventually subsided enough to allow more typical teaching to resume.

For the prospects of future PER work in this area, there may be several sources from which to draw. There are recent developments in PER aimed at facilitating durable changes in physics departments such as the research surrounding Departmental Action Teams (Corbo et al., 2016; Reinholz et al., 2019). It may be fruitful for future digital technologies work to implement some of the recommendations from this departmental-change research or, perhaps more appropriately, the recommendations of PER work on digital technologies could be woven into Departmental Action Team efforts as an integrated aspect of broader institutional change. Another potential place to draw from in future PER work concerning digital technologies is the work of sociologist scholars such as Larry Cuban and Everett Rogers (e.g., Cuban, 2001, 2018; Rogers, 2010), who have already examined technology uptake in
schools and developed theoretical perspectives on the dissemination of innovations. Finally, diSessa (2016) provides a model for the development of education software, called Layered Distributed Development of Educational Resources, that entails iterative collaboration with teachers on the technologies they have a need for in their teaching. Such efforts that involve teachers alongside researchers in the design and implementation of educational innovation may prove to be crucial in the future digital technologies work of PER concerned with technology uptake (see also the promising scholarly work done in the category of ‘education design research’).

**Adaptable constraints in Controllable Worlds**

As part of my last data collection sessions (comprising Dataset 4), I observed participants using either *Algodoo* or the PhET simulation *Pendulum Lab* to explore pendula phenomena. Though I did not ultimately analyze these data in my doctoral work, I did get the sense while collecting them that there was a meaningful shortcoming of the *Algodoo* software when it came to the participants’ discernment of the parameters relating to pendulum motion: *Algodoo* never presented the participants with a streamlined way to vary the pendulum length or angle of their pendula, despite those being among the set of disciplinary relevant aspects for pendula motion. Instead, the participants who used *Algodoo* often estimated the length of their pendula from a scale legend in the bottom of the *Algodoo* scene and usually opted to discuss the position of their pendula in terms of the x- and y-components (which are made readily available by the software). This shortcoming, as I perceived it, stems from the fact that *Algodoo* functions as a less-constrained Controllable World—that is, the software allows for the creation of pendula but is not necessarily optimized for the exploration of pendulum motion in the way that the *Pendulum Lab* is.

This led me to a thought for the potential design feature of future Controllable Worlds resembling *Algodoo*: the software could detect when a pendulum-like object was constructed and adaptably provide sliders for the generalized pendulum variables (such as length, angle, and mass) in the drop-down edit menu? I have mocked up a potential version of this in Figure 50 (next page). A Controllable World that was designed to allow for this functionality would retain the ‘microworldy’ emphasis on construction and messiness, but could also provide users with controls that would present the relevant aspects of a phenomenon such that the variational pattern of contrast could be achieved for those key aspects (similar to what was achieved in Paper IV through the responsive guidance of the researchers). The constraints imposed by the Controllable World could adapt to the use of students. In this way, the Controllable World itself could scaffold students’ exploration of various physics phenomena, allowing students to attend to relevant DoVs for the situation at hand in a manner more typical of *phenomenaria.*
Figure 50. A mockup of a ‘generalized’ edit menu and interface for a pendulum that could be made accessible in a modified Algodoo (bottom) when the software detects a pendulum has been built (top).
Sammanfattning på svenska


Arbetet i denna avhandling representerar min insats i att titta närmare på de processer i meningsskapande som kan ske i ögonblick till ögonblick medan studenter är engagerade med fysikinnehåll genom användandet av kontrollerbara världar. Jämfört med de typer av fysikdidaktiska forskningsprojekt som kan använda sig utav för- och efter-tester för att följa studenters lärande eller
begreppsbemästrande genom utvärderingsverktyg har jag valt att istället fo-
kusera på de mekanismer i meningsskapande som sker mellan ’före’ och ’ef-
ter’. Genom att göra på det här viset har jag kunnat, på meningsfullt sätt, bidra
till den teoretiska bilden av studenters meningsskapande i digitalt rika fysik-
lärandemiljöer. Genom alla studierna som presenteras i den här avhandlingen
har jag konsekvent visat hur användandet av interaktiv teknologi, såsom de
kontrollerbara världarna Algodoo och My Solar System, kan leda till student-
beteenden som är produktiva för fysikundervisning och lärande på sätt som
kan vara oväntat.
I would first and foremost like to thank my wife for her unbelievable help, especially during the final months of stressful thesis preparation. Desirae, you have continued to do more than a partner’s fair share and I am so very grateful to have your love and support. A big thank you also goes to my daughter Elowyn for filling my days with laughter and energy. It has certainly been so much more friendly with three.

To my supervisor, Bor, thank you for your level-headed guidance, for your willingness to work closely with me when needed, and for always believing we had something worthwhile to say. To my other supervisor, Cedric, thank you for lending your expertise to all of my published work and for advocating for my success throughout your extended network of international scholars. Thank you also for connecting Bor and me with Gesche Pospiech in Dresden for our role in the book, *Mathematics in Physics Education*. To Anne, thank you for all your assistance at the office and especially for your invaluable feedback on the final draft of this thesis. To Robin, thank you for your help translating the Swedish summary of this thesis, for all the lovely board game nights, and for all the intellectual stimulation shared over many cups of coffee. To Trevor, thank you for your solidarity in this foreign doctoral journey, for sharing your South African roots, and for accompanying me and my family in our Swedish adventures at every turn. To Moa, thank you for your help with the translations for Paper III, your eagerness to lead us foreigners around Scandinavia, and for your kind friendship throughout the grind. To James, thank you for all the refreshing musical tangents and for your enriching company—always a pleasure and never a bore. To Johanna, thank you for holding me to high standard and for getting me interested in worlds outside of my own experience. To Anders, thank you for blazing a trail for me to follow. To John and Jesper, thank you for your top-notch feedback on my work. To Filip, thank you for all the laughs and for making sure this American keeps on grating. To my past supervisor, Noah Finkelstein, thank you for supporting my data collection at the University of Colorado and for your continued mentorship from afar. I would also like to extend a thank you to all my colleagues at UpRiSE for their collective support.

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School in Subject Didactics (Forskningskola I ämnesdidaktik), and Center for Discipline-Based Education Research (MINT).

To my parents and Jake, thank you keeping me passionate, for showing me the power of quality educators, and for spending so much lovely time with us here in Sweden. Watch the left. Beyond the academic work presented in this thesis, the last four (and a quarter) years have resulted in a grand adventure of personal growth for me. To all of my Uppsala PER colleagues here is Sweden, thank you for the rich community you foster and for your support in making me a better human. To my friends and family back in the U.S., thank you for your virtual support from across the pond and for your patience as I have dedicated myself to this adventure.
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242


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249


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Appendix A

Overview of the work done to the licentiate thesis text
Here I provide an overview of the work done in transforming the text of my licentiate thesis into the final text of this doctoral thesis (in relation to my discussion of the use of previous work in the Preface). Beyond interweaving the new material from the two papers that were published since my licentiate thesis, I have done considerable work to transform the existing text of my licentiate thesis into a new piece of academic writing—often times, outright rewriting sections in accordance with an updated view of my work. This transformation of my licentiate thesis into the text you hold now was motivated by various factors that I came into contact with both during the course of defending my licentiate defense in 2019 and in the intervening months of research work hence. These factors include an attention to how I used nonspecific terminology such as ‘open-ended,’ an expansion of my analytic focus to explicitly include physics teachers, and a new theoretical framing for the digital learning environments which I have come to call ‘Controllable Worlds.’

The first of these factors, a lesson on the importance of terminology, resulted in me being more frugal in my use of some nonspecific words that featured in my licentiate thesis. The most egregious example of these is the word ‘open-ended,’ which I naively included as the tenth word of my licentiate thesis title, but which I proceeded to use inconsistently in the body of that thesis as a vague descriptor for multiple things. For example, as early as the licentiate thesis abstract, I employed the phrases “open-ended inquiry” and “open-ended software” without a clarifying remark to distinguish what I meant in either case. I did not notice the double-use of the word until my public licentiate defense, when the indiscriminate vocabulary was pointed out to me by Dr. Konrad Schönborn, acting as my opponent. I have since made sure to discontinue my use of the term as a descriptor for digital learning environments. In fact, this error in vocabulary was the main impetus for me to better articulate the character of the software I was studying in terms of constraints for the work that followed in Paper IV and V. Ironically, the theoretical classification that I produced to ameliorate my misuse of ‘open-ended’—namely, the constrained/less-constrained distinction for digital learning environments in physics education—now comprises a part of what I see to be a key contribution of this doctoral thesis to technology research in physics education.

A second defining lesson which has shaped the formation of my doctoral kappa has to do with my increased attention to the role of physics teachers alongside students’ use of digital learning environments. In my first three papers and the corresponding licentiate thesis, I focused my analytic attention on small groups of students as they used digital learning environments in what I analyzed as relative isolation. The perspectives I adopted and developed in that research can be synthesized as “the exploration of an ‘ecosystem’ of digitally-rich physics meaning-making” (Euler, 2019, p. 138). This ‘ecosystem’ as it was first conceived involved an interconnected web of students, a digital learning environment, and the physical world, (see Figure i, next page). In Papers I and II, I explored how the participants in my data observably related
to the physical world and a digital learning environment. In Paper III, my attention turned toward the relationship between the participants themselves (against the backdrop of a digital learning environment).

In the time since earning my licentiate degree, however, I have expanded the focus of my work to explicitly acknowledge the role of the physics teacher. In both Paper IV and Paper V, I not only reexamined the relationship between the students and the DLE as was done in Paper I and Paper II, but I also considered the role that a physics teacher might play in such learning situations. This has, of course, had the effect of expanding the relational ecosystem from my licentiate thesis, but it has also given me reason to reconceptualize my work in terms of three broader themes related to physics digital learning environments: what I call ‘Bridging the physical and the formal,’ ‘Embodiment and the making of meaning,’ and ‘The responsive role of the teacher’ (taken up in Chapter 5, Chapter 6, and Chapter 7, respectively) (Figure ii).

Figure i. The relational ‘ecosystem’ of my licentiate thesis, involving a small group of students, a DLE, and the physical world. This ecosystem was explored in various permutations throughout the three papers of my licentiate thesis.

Figure ii. The focuses of the various papers in this thesis as conceptualized amidst a technology-enriched learning ‘ecosystem.’ Three themes are also labelled to illustrate how the papers are grouped in this doctoral thesis.
A third and final factor that has shaped the transition of my licentiate thesis to this doctoral one is my inclusion of a new theoretical framing for digital learning environments as built from a taxonomy by Perkins (1991). Though I will deal with the details of my proposed theoretical framing in Chapters 3 and 8, suffice it to say here that this theoretical perspective involves attending to the function of digital learning environments within broader learning contexts and provides a means for meaningfully characterizing various ‘Controllable Worlds’ digital learning environments used in physics education. Beyond being a useful tool for the interested physics education researcher and physics teacher, I find that this new theoretical framing provides readers of this thesis with a frame within which to conceptually relate the scholarly insights from the five papers of my doctoral work.

Figure iii. The record of work that has gone into transforming the various chapters of my licentiate thesis (on the left side, in black) into the chapters of this doctoral thesis. The orange arrows, broken up by a circular arrow icon, indicate the rewriting/reorganization of material from the licentiate thesis while the green arrows, initiated from a pencil icon, indicate that I wrote of the chapters on the right from scratch.

Taken altogether, these three factors as well as the systematic rewriting/reorganization of my licentiate text have resulted in the doctoral thesis you hold now. In Figure iii I summarize a record of the transformative work that has gone into upgrading the licentiate thesis to this doctoral thesis. Particular details to note include that this Preface, the Introduction (Chapter 1), the
discussion of ‘The responsive role of the teacher’ (Chapter 7), and the consider-
eration of ‘Future work’ (Chapter 10) have all been written from scratch. The
analyses of the papers from my licentiate thesis have now been broken into
three separate chapters based on the three themes of my research (in Chapters
5, 6, and 7) and portions of my licentiate’s literature review were relocated to
respective chapters for the themes to which they apply. The ‘Contributions
and Implications’ chapter and ‘Methodology’ chapter from my licentiate are
the only ones that were simply added to with minimal rewriting/reorganizing.
Every other chapter was either completely overhauled or simply written from
scratch.
Appendix B

Consent forms used for the first dataset
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, *Algodoo*, 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 *Algodoo* software is used alongside a traditional laboratory exercise.

**How can you contribute?**

To examine the ways in which you use digital software such as *Algodoo* 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 *Algodoo* software. Elias will meet with each pair of participants for a short instructional session to familiarize you with the *Algodoo* 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
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, Algodoo, 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 Algodoo 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 Algodoo 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 Algodoo 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 C

Consent forms used for the second dataset
Obveščeno soglasje k sodelovanju v raziskavi

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


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 intervjuilih 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.


8. V primeru morebitnih dodatnih vprašanj se lahko obrnete na raziskovalca Bora Gregorciča (bor.gregorci@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 pravolitev 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 D

Consent forms used for the third dataset
Medgivande att delta i en vetenskaplig studie

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

Villkor för deltagande


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 att 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 läst härdisk och ingen obehörig person kommer att ha tillgång till materialet. Resultatet av denna studie kan komma att publiceras i akademiiska 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
Ytterligare medgivande för användning av ocensurerad videodata

(insamlad som del av ett forskningsprojekt om användning av digitala verktyg inom fysikinlärning. Kontaktpersoner Elmer Rådahl och Bor Gregorcic)

Efter slutet 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 kommunikerade 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.gregorvic@physics.uu.se
Appendix E

Consent forms used for the fourth dataset
Consent to participation in a scientific study

In collaboration with researchers at the University of Colorado Boulder, the Physics Education Research Group from Uppsala University is conducting a research project to explore the ways in which digital software is used as a tool in learning physics. We are interested in how you, your peers, and other physics learners like you interact with digital tools while doing physics!

Conditions of participation

We would like to record you and a partner completing a physics task while you use a digital tool. As a participant of this study, you will be asked to attend a two-hour session where the researcher(s) quickly teaches you how to use the software and then you complete a physics activity with one other participant (while under the observation of the researcher). Following the completion of the activity, a short discussion will take place where you reflect on the activity. The software training, physics activity, and subsequent discussion 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 United States and 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, likeness, 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. 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 (unless you provide permission otherwise). 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. You can also 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.

In accordance with research law, we are required to archive research data. The data 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 data. The results from this study may be published in academic journals and in a dissertation. The study may 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 digital tools 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 your ideas during the activity you just completed. 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 from today could prove to be especially useful and 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.

Additional 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 F

Example transcript from the first dataset
<table>
<thead>
<tr>
<th>Timestamp</th>
<th>R1</th>
<th>R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:56:12</td>
<td>So yeah, you can-you can just choose whatever technique you want. It's up to you to decide what 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.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Interrupting) So maybe-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-use the physical OR you use the non-physical way because you cannot merge virtual world and non-virtual world.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Draws a rectangle on the Smartboard</td>
<td></td>
</tr>
</tbody>
</table>

**Talk**

- you can just choose whatever technique you want. It's up to you to decide what 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.

**Gesture**

- use the physical OR you use the non-physical way because you cannot merge virtual world and non-virtual world.
<table>
<thead>
<tr>
<th>Timestamp</th>
<th>S1 Talk</th>
<th>S1 Gesture</th>
<th>Interaction with Objects</th>
<th>S2 Talk</th>
<th>S2 Gesture</th>
<th>Interaction with Objects</th>
<th>R1</th>
<th>R2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(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 more in general.</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>(Pauses again) now draws a circle above the tilted rectangle</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>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 slope?</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td>So you want to move things around, you need the pen tool... when it's PAUSED... when it's paused.</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>And if you wanna do you want this rectangle to be there?</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Yes.</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>Then you can just double click on it</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Tries to double tap the rectangle</td>
<td></td>
<td></td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Successfully double clicks the rectangle, opening a drop-down menu.</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>...Uh again. And then go to geometry actions... about, fourth from the bottom.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timestamp</td>
<td>S1</td>
<td>S2</td>
<td>R1</td>
<td>R2</td>
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<td></td>
<td>Talk</td>
<td>Gesture</td>
<td>Interaction with Objects</td>
<td>Talk</td>
<td>Gesture</td>
<td>Interaction with Objects</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Points to the “geometry actions” bar on the drop down menu (on the Smartboard)</td>
<td>Yeah. And then select geometry actions.</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>Above the (indistinguishable).</td>
<td>And then glue to the background. Yeah.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ah.</td>
<td>And now it won’t... uh fly- it won’t fall down. It’s part of the environment now.</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>K. Lets... try this.</td>
<td>Presses the play button to run the simulation</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>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</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>About here, right?</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Yeah something like that.</td>
<td>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.</td>
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<td></td>
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<tr>
<td></td>
<td>Okay.</td>
<td>Does that make sense?</td>
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<tr>
<td>Timestamp</td>
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<td>S2</td>
<td>R1</td>
<td>R2</td>
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<td></td>
<td>Talk</td>
<td>Gesture</td>
<td>Interaction with Objects</td>
<td>Talk</td>
<td>Gesture</td>
<td>Interaction with Objects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>So then we should add...</td>
<td>Selects rectangle tool on the Smartboard</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>...another... rectangle.</td>
<td>Draws a small rectangle next to the tipped rectangle drawn by 21102</td>
<td>Bigger. Maybe? Mm, okay.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>That doesn't really matter.</td>
<td>Moves new rectangle so that the top-left corner is intersecting the top right corner of the tilted rectangle.</td>
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</tr>
<tr>
<td></td>
<td>Continues moving the rectangle.</td>
<td>Moves hand downward while gesturing toward the second rectangle.</td>
<td>And if you glue things to the background, um... they can overlap each other.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Continues moving the rectangle.</td>
<td>Move it down. ...A bit. Yeah.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Opens drop down menu and selects &quot;glue to background&quot; option</td>
<td>Glue it.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alright.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landed about, here I would say.</td>
<td>Points to spot on the board where the circle landed on the ground.</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Timestamp</td>
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<td>S2</td>
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<td></td>
<td>Talk</td>
<td>Gesture</td>
<td>Interaction with Objects</td>
<td>Talk</td>
<td>Gesture</td>
<td>Interaction with Objects</td>
<td>R1</td>
<td>R2</td>
</tr>
<tr>
<td></td>
<td>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.</td>
<td>(Laughing) Do not remove Earth.</td>
<td>(Laughs)</td>
<td>So...</td>
<td>(Interuppting) 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.</td>
<td>Picks up the physical ramp and tilts it to demonstrate their point, holding the ramp in the upward position.</td>
<td>Then we-</td>
<td>Gestures with hand to show moving all of the shapes upward on the board.</td>
</tr>
<tr>
<td></td>
<td>Holds the ramp.</td>
<td>(Interuppting) Yeah. What's the relationship between how high the ball- the puck starts and how far it goes?</td>
<td>Tries to select all of the shapes on the board by encircling them with their finger.</td>
<td>Puts the ramp down.</td>
<td>Tries again.</td>
<td>So not-</td>
<td>Pen.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Points vaguely toward the top of the tool bank on the board.</td>
<td>Pen...</td>
<td>Pen tool.</td>
<td>I want to mark all them.</td>
<td>Selects pen tool and then encircles all of the shapes.</td>
<td>Mm hm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timestamp</td>
<td>S1</td>
<td>S2</td>
<td>R1</td>
<td>R2</td>
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<td></td>
<td><strong>Talk</strong></td>
<td><strong>Gesture</strong></td>
<td><strong>Interaction with Objects</strong></td>
<td><strong>Talk</strong></td>
<td><strong>Gesture</strong></td>
<td><strong>Interaction with Objects</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>But that would just make it... increase upwards.</td>
<td>Moves both hands upward while holding them horizontally to show &quot;upwards but not tilting&quot;</td>
<td>Yeah but I want to move all them upwards.</td>
<td>Points and moves arm upward</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yeah because-</td>
<td>Or down-</td>
<td>Moves arm downward</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>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.</td>
<td>Picks the physical ramp up again and lifts one end to show the ramp rotating rather than translating upward</td>
<td>Mm.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>So we just-</td>
<td>Okay.</td>
<td>Looks back at the Smartboard.</td>
<td>Yeah not the- the overall height above the floor of the...</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>So the table stays where it is.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Yeah so instead, do like...</td>
<td>Selects the rotate tool and then selects the &quot;pink&quot; rectangle</td>
<td>Rotates the rectangle about the center point.</td>
<td>Just rotate that one.</td>
<td>Points vaguely toward the larger rectangle (pink one)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Uhh...</td>
<td>Continues rotating and then stops. Presses the undo button</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Let’s see... Is there any way for this software to change the center of rotation?</td>
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</tr>
<tr>
<td>Timestamp</td>
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<td>Interaction with Objects</td>
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<td></td>
<td>I don't think so, is there?</td>
<td>Tries to rotate the rectangle again.</td>
<td>Where would you like the center of rotation to be then?</td>
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<tr>
<td></td>
<td>Uhh...</td>
<td>Points to the bottom of the physical ramp.</td>
<td>Down here.</td>
<td></td>
<td></td>
<td>Ah okay.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>So that we can... mimic it in the real world.</td>
<td>Gestures with both palms flat, moving in opposite directions up and down to suggest tilting</td>
<td></td>
<td></td>
<td>Mm hmmm.</td>
<td>Mm.</td>
<td></td>
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<td></td>
<td>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.</td>
<td></td>
<td>I think, there- we can b- so we can try something I'm not sure it will work but there's one way you could do this.</td>
<td></td>
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<tr>
<td></td>
<td>Uh huh?</td>
<td>Still examines the menu.</td>
<td>K.</td>
<td></td>
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<td></td>
<td>Selects the &quot;geometry actions&quot; tab and bends to look at the options</td>
<td>Moves to tap outside the menu to get rid of it</td>
<td>And that is if you zoom in to that end of the, uh-</td>
<td></td>
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<tr>
<td></td>
<td>Ah wait, here.</td>
<td>Places center axle on the rectangle.</td>
<td></td>
<td></td>
<td></td>
<td>So that-</td>
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<tr>
<td></td>
<td>Tries to select just the center axle.</td>
<td></td>
<td></td>
<td>Yeah that was exactly what I was thinking. But you... so how did you find this? You noticed this before.</td>
<td></td>
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<tr>
<td></td>
<td>No. I just guessed.</td>
<td>Continues to try to select the axle.</td>
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<td>Interaction with Objects</td>
<td>S2</td>
<td>Talk</td>
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<td></td>
<td></td>
<td></td>
<td>Ah okay. So-</td>
<td></td>
<td></td>
<td></td>
<td>So this is CENTER axle.</td>
</tr>
<tr>
<td>Geometry actions...</td>
<td></td>
<td></td>
<td></td>
<td>Clicks through the menu like before to show where the center axle came from</td>
<td></td>
<td></td>
<td></td>
<td>Yeah.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>So if you remove this one... If you...</td>
<td></td>
<td></td>
<td></td>
<td>Take that one.</td>
</tr>
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<td></td>
<td>Tries to select the center axle, then selects pen tool.</td>
<td></td>
<td></td>
<td></td>
<td>Tries to select the center axle again, and then the pen tool. No-</td>
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<td></td>
<td></td>
<td>Tries to move the axle to the upper right corner of the rectangle.</td>
<td></td>
<td></td>
<td></td>
<td>After a couple of tries finally gets the axle to move.</td>
</tr>
<tr>
<td>Whoops. Let’s just move that one... And then take this one... and move it, there.</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>Oh my gosh...</td>
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<td></td>
<td>Deselects the axle, moves the smaller rectangle out of the way, and then reselcts the axe to place it on the corner of the larger rectangle. Mm hmm.</td>
<td></td>
<td></td>
<td></td>
<td>And then move this one and have it above the center axis.</td>
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<td></td>
<td>Moves the smaller rectangle back to overlap the end of the larger (slipped/pink) rectangle</td>
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<tr>
<td><strong>01:02:54</strong></td>
<td>This works perfectly!</td>
<td>Selects the larger rectangle and rotates it around the new point of rotation as desired</td>
<td>And...</td>
<td>Selects the rotate tool</td>
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<td></td>
<td>So now we can increase this one as much as we would like and the only thing we'll have to do is-</td>
<td>Moves the angle of the rectangle preliminary orientation</td>
<td>And try to rotate.</td>
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<td></td>
<td>Yes.</td>
<td>Selects the pen tool and moves the circle upward</td>
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<td></td>
<td>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...</td>
<td>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</td>
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<td></td>
<td>What does this one do?</td>
<td>Selects some buttons from a side menu of Smartboard actions</td>
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<td></td>
<td>Smartboard features.</td>
<td></td>
<td>Oh those are like, Smartboard-</td>
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<td></td>
<td>So is there any to like paint colors that are nothing, are just colors.</td>
<td>Moves hands with fingers splayed in circular motion while saying “paint colors”</td>
<td>Oh yeah.</td>
<td>So yeah...</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Yeah.</td>
<td></td>
<td>Oh to just mark something?</td>
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<td>Interaction with Objects</td>
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<tr>
<td>01:03:47</td>
<td>Double clicks the circle, and examines the drop down menu until they find the &quot;plot&quot; option</td>
<td>Unfortunately, this software doesn't do that.</td>
<td>(Overlapping)</td>
<td>Yeah...</td>
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<td></td>
<td>You can plot.</td>
<td>Points to the graph that they have produced for 21102 to see</td>
<td>But you can actually make STUFF draw stuff.</td>
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<td></td>
<td>Yeah.</td>
<td></td>
<td>Make stuff draw stuff?</td>
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<td></td>
<td>Points to the graph that they have produced for 21102 to see</td>
<td>Examines the plot menu.</td>
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<td></td>
<td>Clicks on one of the axis values and examines the options</td>
<td>Yeah. Stuff that moves there can draw stuff. It can...</td>
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<td></td>
<td>Hovers their hand over the options</td>
<td>Yeah. So you can track actually where...</td>
<td>So you can track where the ball went.</td>
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<td></td>
<td>Selects one of the options.</td>
<td>On the background.</td>
<td>On the background as it plays. Yeah yeah.</td>
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<td>(Overlapping)</td>
<td>And we could also do... this.</td>
<td>Points toward the graph on the board</td>
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<td></td>
<td>Hovers their hand over the options</td>
<td></td>
<td>Mm hmm.</td>
<td></td>
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<td>Which would show us... We need the position-y, otherwise we will not be...</td>
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<td>Clicks on the position-y option and then changes the other axis to the desired option (position-x)</td>
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<td>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</td>
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<td></td>
<td></td>
<td>Something like that... I think.</td>
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<td></td>
<td></td>
<td></td>
<td>Aaand start?</td>
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<td></td>
<td></td>
<td></td>
<td>Yeah.</td>
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<td></td>
<td>Presses the play button to start the simulation, then pauses the simulation when the ball has circle has rolled away.</td>
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<td></td>
<td>Ahh, let's see. If we look closer at this.</td>
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<td>Bends to examine the graph from closer up</td>
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<td>Clicks on the graph region to select the specific data</td>
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<td></td>
<td></td>
<td></td>
<td>Here.</td>
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<td></td>
<td>Points to the spot on the graph where they think the circle hit the ground</td>
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<td></td>
<td></td>
<td></td>
<td>Yeah there.</td>
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<td>Steps back from the board.</td>
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<td></td>
<td></td>
<td>We can see that...</td>
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<td></td>
<td></td>
<td>We have to look at it from here to there.</td>
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<td>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</td>
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<td></td>
<td>Hit's the ground there. That's what we want to get.</td>
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<td></td>
<td>Points to the spot on the graph where they think the circle hit the ground.</td>
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<td>Interaction with Objects</td>
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<tr>
<td>Yeah, we want to know the distance... here.</td>
<td>Points to the table, places their hands together, and then spreads them apart to show where the distance starts and stops</td>
<td></td>
<td>Mm hmm.</td>
<td>Correct.</td>
<td></td>
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<tr>
<td>Yeah. Ehh... (Long pause) 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?</td>
<td>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</td>
<td></td>
<td>Mm hmm. Is there a question?</td>
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<tr>
<td>Uhh, I think so. I'm not... I don't really know how to look at this graph to determine-</td>
<td>Leans forward to see the graph more closely and then resizes the window of the graph to a larger size by dragging the corner</td>
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<td>I mean here it says ten meters, there.</td>
<td>Points to the point on the x-axis labelled 10</td>
<td></td>
<td>So, what is this graph displaying to you?</td>
<td>Yeah.</td>
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<td></td>
<td>The y-position and the x-position.</td>
<td>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</td>
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<td></td>
<td>But what I can't really see is where the x-position's zero point is. That should be there.</td>
<td>Points to the origin of the graph on the axes</td>
<td></td>
<td></td>
<td>Mm hmm.</td>
<td></td>
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<tr>
<td></td>
<td>But it doesn't show much more.</td>
<td>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)</td>
<td></td>
<td></td>
<td></td>
<td>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?</td>
<td></td>
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<td></td>
<td>Yeah it describes exactly where the ball has been. It shows the path of the ball.</td>
<td>Traces out the shape of the path of the circle with one hand</td>
<td></td>
<td></td>
<td></td>
<td>Mm hmm.</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>So in space right?</td>
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<tr>
<td></td>
<td>In space, yes.</td>
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<td>Interaction with Objects</td>
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<tr>
<td>So can you- I think you can actually see where the x zero is then.</td>
<td>Yeah when it starts rolling on the other-</td>
<td>Drags the graph window out of the way so that the rectangles can be seen.</td>
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<tr>
<td>Mm hmm. So.</td>
<td>When it starts rolling on that one.</td>
<td>Points to intersection of the two rectangles.</td>
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<tr>
<td>And where would you like it to be?</td>
<td>No. We want it on the end... there.</td>
<td>Drags the graph window again so that the end of the small rectangle is visible and then points to this spot on the rectangle.</td>
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<tr>
<td>Okay.</td>
<td>Traces around all of the shapes on the board to select all of them</td>
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<td>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.</td>
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<tr>
<td>Timestamp</td>
<td>S1</td>
<td>S2</td>
<td>R1</td>
<td>R2</td>
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<td></td>
<td>Talk</td>
<td>Gesture</td>
<td>Interaction with Objects</td>
<td>Talk</td>
<td>Gesture</td>
<td>Interaction with Objects</td>
<td>So if you move this graph up-</td>
<td>Yeah... Sorry (Stands up and moves the graph out of the way of the bottom menu where the grid button resides)</td>
</tr>
<tr>
<td></td>
<td>It's in the bottom. This grid. Yeah</td>
<td></td>
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<td></td>
<td>(Clicks on the grid button and then moves the graph window all the way to the left again)</td>
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<tr>
<td></td>
<td>Ah. And this is the zero then?</td>
<td>Points to the where the two rectangular shapes intersect one another</td>
<td></td>
<td>So you can actually see...</td>
<td></td>
<td></td>
<td>You can see.</td>
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<td></td>
<td>So then we just... take that one and move it there.</td>
<td>Drags all of the shapes together so that the rightmost side of the smaller rectangle is on the grid line corresponding to the zero point on the graph</td>
<td></td>
<td>Mm.</td>
<td></td>
<td></td>
<td>Yes.</td>
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<td></td>
<td>Uhh... before we do that we should reset it though so we have the ball.</td>
<td>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</td>
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<td></td>
<td>Uhh... what happened?</td>
<td>Pauses halfway through selecting and then finishes after figuring out what was going on with the grid turned on</td>
<td></td>
<td>So when you have the grid on it makes you draw on the grid too... but it looks like it worked.</td>
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<tr>
<td>Timestamp</td>
<td>S1 Talk</td>
<td>Gesture</td>
<td>Interaction with Objects</td>
<td>S2 Talk</td>
<td>Gesture</td>
<td>Interaction with Objects</td>
<td>R1</td>
<td>R2</td>
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<td></td>
<td>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</td>
<td></td>
<td>This works.</td>
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<td></td>
<td>Yeah. And from here we can...</td>
<td></td>
<td>Try it again?</td>
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<td></td>
<td>Yeah.</td>
<td></td>
<td></td>
<td>Drags the window of the graph upward so that the data can be seen.</td>
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<td></td>
<td>Just... start. See what happens.</td>
<td></td>
<td>Presses the play button to start the simulation.</td>
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<td></td>
<td>Then we can... measure... the x-position position and see that it went</td>
<td></td>
<td>Watches the simulation run then pauses the simulation</td>
<td></td>
<td></td>
<td>Watches the simulation run.</td>
<td></td>
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<tr>
<td></td>
<td>Two point seventy-five meters</td>
<td>Shakes one hand for the iconic gesture of approximately</td>
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<td>01:09:21</td>
<td>With that much tilting of the ramp</td>
<td>Tilts the same hand downward from an elevated wrist to show a downward tilt</td>
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</table>
Appendix G

Example transcript from the third dataset
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

ju alltid ha en motkraft mot var den andra planet är.
always have a counterforce toward where the other planet is.
points his index fingers upward  (Figure 2a)

ju alltid ha en motkraft mot var den andra planet är.
always have a counterforce toward where the other planet is.
pushes himself back into his chair and looks at IWB
looks back to Beth

3 Beth  Ja.  (1)
Yeah.  (1)
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

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.  (1)
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)

väger mindre än mig (1)
weigh less than me
puts hand down and looks to Beth
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
(4, left)
turns back to Adam and extends her hands toward him
(4, right)

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
(4, right) they fully extend their arms
(Figure 4, right)

Beth: Mhm. (1)
Mhm.

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 (5b, left)
Beth: Än mig than me
rotte runt här för då kommer ju bara rama ut ditåt för att
då finns det ingenting som håller kvar dig, then there is nothing holding you anymore.
drops her hands from the dance and looks to the IWB

Adam: Det är ju- är de riktade? Och ser du någon likhet med-
It’s like- they are directed? And do you see any similarities with-

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
försöka 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-

Adam: Altså, de är ju riktade mot varandra hela tiden. (1)
I mean, they are directed toward each other all the time.

Beth: Nåe, här är de ju riktade ifrån varandra.
No, here they are directed away from each other.

Adam: Nä.
No.

Beth: Nehe?
No?

Adam: För du ser ju att (5)
Because you can see

Ser du nu är de
See, now they are

riktade så. (1)
directed like so.

Det är därför de går- går omlott "ohörbart"
That is why they go- go around "inaudible"

looks from the IWB to Beth

looks back to the IWB and traces a small circle with his hand

looks back to Beth while continuing to trace a circle

Beth: Jaaaaa
Yeaaaah

Adam: 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

Beth: Och så riktas de mot varandra så jas (1)
And then they are directed toward each other, so yeah

steps up to the IWB and follows the shape of the orbits
steps back from the IWB
Så här riktas de mot varandra. (1)
So here they are directed toward each other.

Adam
follows the stars as they orbit in the simulation with his
fingers pointed toward each other again as Beth watches

Beth
Mot varandra. Okej. (4)
Toward each other. Okay.

Adam
Så än deras krafter kan representeras som våra händer liksom
then their forces can be represented as our hands kinda.

Beth
Mm.

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

Beth
Jag måste ha större bana!
I must have a larger orbit!

Adam
Exakt.
Exactly.

Beth
Snyggt!
Nice!
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