Students Learning Science:  
Representation Construction in a Digital Environment

by

Constance Cirkony  
B.Sc., B.Ed., M.A.

Submitted in fulfilment of the requirements for the degree of  
Doctor of Philosophy

Deakin University  
October 2018
I am the author of the thesis entitled

*Students Learning Science: Representation Construction in a Digital Environment* submitted for the degree of *Doctor of Philosophy*

This thesis may be made available for consultation, loan and limited copying in accordance with the Copyright Act 1968.

'I certify that I am the student named below and that the information provided in the form is correct'

**Full Name:** Constance Lee Cirkony

**Signed:** [Signature Redacted by Library]

**Date:** March 8, 2019
I certify the following about the thesis entitled (10 word maximum)

**Students Learning Science: Representation Construction in a Digital Environment** submitted for the degree of **Doctor of Philosophy**

a. I am the creator of all or part of the whole work(s) (including content and layout) and that where reference is made to the work of others, due acknowledgment is given.

b. The work(s) are not in any way a violation or infringement of any copyright, trademark, patent, or other rights whatsoever of any person.

c. That if the work(s) have been commissioned, sponsored or supported by any organisation, I have fulfilled all of the obligations required by such contract or agreement.

d. That any material in the thesis which has been accepted for a degree or diploma by any university or institution is identified in the text.

e. All research integrity requirements have been complied with.

'I certify that I am the student named below and that the information provided in the form is correct'

**Full Name:** Constance Lee Cirkony

**Signed:** [Signature Redacted by Library]

**Date:** October 10, 2018
Acknowledgements

This thesis was a natural extension of my Master of Arts research, bridging my interest in the environment as a meaningful context for learning with the creative and iterative process of meaning making that drives scientific exploration. This project involved a collaboration of participants, researchers, and supporters whom I gratefully acknowledge for their support.

Firstly, I would like to thank my research school who welcomed me into their community; and my research participants, the teacher and students who and shared with me their genuine interest in learning and participating in this project.

Thanks to my supervisory team: Russell Tytler, for his guidance in the art of the academic argument, insightful comments, and his leadership in the academy; and Peter Hubber, for his guidance in the representation construction process and how it translates to the teaching and learning of physics. I would also like to acknowledge the Science, STEM & Environmental Education team across the Deakin campuses, who provided their wisdom and encouragement throughout the process, and to Peta White who initially introduced me to this project and the Deakin team. I also acknowledge Shaaron Ainsworth, who welcomed me to her Learning Sciences Institute at the University of Nottingham and provided insights into representations and technology enhanced learning; and to the European Science Education Research Association for providing a travel grant to support this endeavour.

I acknowledge my family and friends for their patience, curiosity, and support as I embarked on this journey from far and away; and to John Kenny, who was always up for a conversation about representations and generously offered his time and insights by reading my thesis.

Thanks to the Deakin graduate student administrative support team who offered both professional and personal guidance throughout this journey; and to my fellow researchers-in-training, who artfully incorporated time to celebrate and reflect; And to the team at ATSE, who welcomed me into their community.

I acknowledge Daxx Longaphie for developing the graphics in Figure 3.1 and 4.8; and Marie Christodulaki, who provided copyediting and proofreading services according to the guidelines laid out in the university-endorsed national ‘Guidelines for editing research theses’.

Finally, I would like to acknowledge the Australian Research Council for funding the digital inquiry project, with which my PhD research is associated.
## Table of Contents

Acknowledgements .........................................................................................i

Table of Contents ..........................................................................................ii

List of Tables .................................................................................................vi

List of Figures ...............................................................................................vii

List of Abbreviations ....................................................................................x

Abstract ........................................................................................................xi

Chapter 1. Introduction ..................................................................................1

1.1 Background .............................................................................................1
   1.1.1 Representation construction pedagogy and digital technologies ........2

1.2 Significance .............................................................................................4

1.3 Structure of the Thesis ...........................................................................6

Chapter 2. Literature Review .........................................................................11

2.1 The Challenges of Teaching and Learning Science ...............................11
   2.1.1 Why is learning science challenging? ...........................................12
   2.1.2 Learning scientific concepts .......................................................13
   2.1.3 Contemporary perspectives on learning ....................................14
   2.1.4 The multimodal language of science .........................................18

2.2 Inquiry-Based Representation Construction .......................................22
   2.2.1 Philosophical and theoretical underpinnings of RCA ..................22
   2.2.2 Learning through different modes and multiple representations ....25
   2.2.3 The role of inquiry in RCA ........................................................25
   2.2.4 The framework and principles of RCA .......................................27

2.3 Digital Learning .....................................................................................29
   2.3.1 Global trends and opportunities .................................................30
   2.3.2 Digital learning environments ....................................................32
   2.3.3 Digital technologies for learning science .................................40

2.4 Outline of my Research Focus ...............................................................44

Chapter 3. Methodology ..............................................................................46

3.1 Rationale for Research Approach ............................................................46
   3.1.1 Qualitative research ...................................................................46
   3.1.2 Ethnography ...............................................................................48
   3.1.3 Case study ..................................................................................48

3.2 Research Design .....................................................................................50
   3.2.1 Research setting .........................................................................50
   3.2.2 Theoretical framework: Distributed cognition .............................59
   3.2.3 Data generation .........................................................................67
   3.2.4 Data analysis .............................................................................76
   3.2.5 Data quality ..............................................................................80
   3.2.6 Role of researcher and participants ..........................................84
   3.2.7 Ethical considerations ...............................................................85

3.3 Chapter Summary ...................................................................................87
Chapter 4. The Unit as Experienced

4.1 Reconstructing the Unit ................................................................. 88
   4.1.1 Reconstructing lessons in the unit ............................................. 95
   4.1.2 Analytical perspectives of the DLE ........................................... 96

4.2 Part I: Blended Interactions ........................................................... 98
   4.2.1 Coding for face-to-face and online interactions .......................... 98
   4.2.2 Summary of Part I ................................................................. 107

4.3 Part II: Distributed Social and Material Interactions ......................... 107
   4.3.1 Coding for social (i.e., dialogic) interactions ............................. 109
   4.3.2 Summary of social interactions .............................................. 115
   4.3.3 Coding for material interactions ............................................ 116

4.4 Chapter Summary ........................................................................ 129
   4.4.1 The distributed cognitive perspective ...................................... 130

Chapter 5. Students’ Experience Across the Modules ............................. 132

5.1 Developing a Case Perspective of the Unit – as Experienced ............... 132

5.2 Understanding Prior Knowledge and Establishing the Context (Modules 1–4) 133
   5.2.1 Conceptual focus of the unit ................................................... 133
   5.2.2 Understanding students’ prior knowledge (Module 1) ................. 134
   5.2.3 Establishing the context (Modules 2–4) .................................... 137

5.3 Engaging with the Concepts (Modules 5–8) .................................... 141
   5.3.1 Module 5: Temperature and thermal energy ............................. 141
   5.3.2 Module 6: Heat transfer through conduction ............................ 158
   5.3.3 Module 7: Heat transfer through convection ............................ 168
   5.3.4 Module 8: Heat transfer through radiation ............................... 179

5.4 Chapter Summary ........................................................................ 187
   5.4.1 Generative features the learning environment in supporting RCA 187
   5.4.2 The learning sequences and the nature of SGRs ....................... 191

Chapter 6. Students’ Experience of the Sustainable House Inquiry .......... 196

6.1 Applying a DCog Framework to Understand Learning During a Complex Task 197
   6.1.1 Design of the task ................................................................. 198
   6.1.2 Assessing the nature of student reasoning ............................... 200

6.2 Students’ Engagement with the Task: Planning ............................... 203
   6.2.1 Developing the hypothesis around the inquiry questions ............ 204
   6.2.2 The method ......................................................................... 209
   6.2.3 Summary of the planning stage ............................................ 213

6.3 Students’ Engagement with the Task: The Experiment .................... 214
   6.3.1 Equipment and set up .......................................................... 215
   6.3.2 First series of control, foil outside, and foil inside trials .......... 216
   6.3.3 Second series of control, foil outside, and foil inside trials .......... 226
   6.3.4 Summary of the experiment stage ...................................... 235

6.4 Students’ Engagement with the Task: Writing the Report .................. 239
   6.4.1 The report .................................................................. 244

6.5 Chapter Summary ........................................................................ 247
Chapter 9. Conclusion........................................................................................................367

9.1 Contributions to the Literature.................................................................................. 367
  9.1.1 The affordances of a DLE in supporting RCA.......................................................368
  9.1.2 Considerations for design of digital RCA learning sequences..............................369
  9.1.3 Insights from a distributed cognitive perspective on inquiry tasks ......................370

9.2 Implications and Future Research............................................................................ 372
  9.2.1 Additional considerations in designing digital RCA learning sequences...............372
  9.2.2 Use and design of online learning platforms..........................................................373
  9.2.3 Considerations for curriculum and assessment.....................................................376
  9.2.4 Considerations for student engagement in science and STEM............................378

9.3 Methodological Reflections...................................................................................... 378

References ...................................................................................................................... 381

Appendices ..................................................................................................................... 402
List of Tables

Table 3.1  STILE Modules, Key Ideas, and Synopsis – as Planned .......... 54
Table 3.2  Data Set and the Amount of Digital Storage ....................... 76
Table 4.1  Sequence of Modules, Description of the Lesson, Activities, and Data Generated ................................................................. 89
Table 4.2  Guidelines for Applying Blended Interactions Codes .............. 99
Table 4.3  Comparison of Time Spent in Each Domain (in minutes) for each of the Two Groups .......................................................... 106
Table 4.4  Guidelines for Applying Dialogue Codes ........................... 110
Table 4.5  Comparison of Time Spent in Each Domain (in minutes) for each of the Two Groups .......................................................... 114
Table 4.6  Guidelines for Applying Technology Codes ....................... 118
Table 4.7  Comparison of Time Spent in Each Domain (in minutes) for each of the Two Groups .......................................................... 124
Table 4.8  List of Digital and Non-digital Representations Students Accessed and Generated During the Unit ........................................... 128
Table 5.1  The Key ideas embedded in each the Introduction, Climate Change, and Energy Transfer Modules Respectively ......................... 134
Table 7.1  Pre- and Post-Test Results .................................................. 254
Table 7.2  Simplified Criteria to Assess Learning Gains in Multiple Choice Questions ................................................................. 255
Table 7.3  Multiple Choice Questions, Concepts, and Students’ Responses with Correct Answers in Boldface ........................................ 256
Table 7.4  Structure of Scientific Explanations used as Criteria for Scoring each of the three Open-ended Questions .................................. 262
Table 7.5  Summary of Levels of Representational Competence .......... 264
Table 7.6  Summary of the Case Group .............................................. 280
Table 8.1  Designing Learning Sequences to Support Representation-Focused Approaches ................................................................. 362
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Elements in a distributed cognitive system as they align with my methods</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>for data generation.</td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>GoPro camera.</td>
<td>71</td>
</tr>
<tr>
<td>4.1</td>
<td>Bianca’s group timeline in the conduction lesson.</td>
<td>101</td>
</tr>
<tr>
<td>4.2</td>
<td>Bianca’s group timeline in the convection lesson.</td>
<td>101</td>
</tr>
<tr>
<td>4.3</td>
<td>Ina’s group timeline in the radiation lesson.</td>
<td>101</td>
</tr>
<tr>
<td>4.4</td>
<td>Class viewing the video on how to do the convection investigation (left),</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td>and students constructing representations in the radiation module in STILE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and in their project books (right).</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>Timelines in SH Inquiry planning lesson. Note that parts a) and b) are</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>sequential.</td>
<td></td>
</tr>
<tr>
<td>4.6</td>
<td>Ina’s group timeline in SH Inquiry experiment lesson.</td>
<td>104</td>
</tr>
<tr>
<td>4.7</td>
<td>Ina’s group timeline in SH Inquiry report writing lesson.</td>
<td>104</td>
</tr>
<tr>
<td>4.8</td>
<td>Distributed elements including social and material interactions.</td>
<td>108</td>
</tr>
<tr>
<td>4.9</td>
<td>Bianca’s group timeline in conduction lesson.</td>
<td>111</td>
</tr>
<tr>
<td>4.10</td>
<td>Bianca’s group timeline in convection lesson.</td>
<td>111</td>
</tr>
<tr>
<td>4.11</td>
<td>Ina’s group timeline in radiation lesson.</td>
<td>111</td>
</tr>
<tr>
<td>4.12</td>
<td>Timeline in SH Inquiry planning lesson. Note that parts a) and b) are</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td>sequential.</td>
<td></td>
</tr>
<tr>
<td>4.13</td>
<td>Ina’s group timeline in SH Inquiry experiment lesson.</td>
<td>113</td>
</tr>
<tr>
<td>4.14</td>
<td>Ina’s group timeline in SH Inquiry report writing lesson.</td>
<td>113</td>
</tr>
<tr>
<td>4.15</td>
<td>Bianca’s group timeline in the conduction lesson.</td>
<td>120</td>
</tr>
<tr>
<td>4.16</td>
<td>Bianca’s group timeline in the convection lesson.</td>
<td>120</td>
</tr>
<tr>
<td>4.17</td>
<td>Ina’s group timeline in the radiation lesson.</td>
<td>120</td>
</tr>
<tr>
<td>4.18</td>
<td>Timelines in SH Inquiry planning lesson. Note that parts a) and b) are</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>sequential.</td>
<td></td>
</tr>
<tr>
<td>4.19</td>
<td>Ina’s group timeline in SH Inquiry experiment lesson.</td>
<td>122</td>
</tr>
<tr>
<td>4.20</td>
<td>Ina’s group timeline in SH Inquiry report writing lesson.</td>
<td>122</td>
</tr>
<tr>
<td>5.1</td>
<td>Energy word clouds constructed by Ina (above) and Clara (below).</td>
<td>122</td>
</tr>
<tr>
<td>5.2</td>
<td>Energy mind maps constructed by Ina (above) and Megan (below).</td>
<td>135</td>
</tr>
<tr>
<td>5.3</td>
<td>Mind maps on Greenhouse Gases constructed by Clara (above) and Megan (below).</td>
<td>136</td>
</tr>
<tr>
<td>5.4</td>
<td>Mind maps on Sustainable Housing constructed by Clara (above) and Megan</td>
<td>138</td>
</tr>
<tr>
<td></td>
<td>(below).</td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>Activity 5.2 instructions for the representational challenge.</td>
<td>140</td>
</tr>
<tr>
<td>5.6</td>
<td>The case group’s responses to the six representational challenges.</td>
<td>144</td>
</tr>
</tbody>
</table>
Figure 5.7. Class variations of representations of a lump of plasticine that can be changed into a different shape (i.e., Q2). .......................................................... 147
Figure 5.8. Class variations of representations of a lump of plasticine that can be changed into a different shape (i.e., Q2). .......................................................... 149
Figure 5.9. Screenshot of the video of animation in Activity 5.4. ................. 152
Figure 5.10. The case group’s response to representational challenge 5.4 ...... 153
Figure 5.11. Screenshots of the video of Kinetic Energy, Temperature, Thermal energy, and Heat in Activity 5.5 (read left to right)............................... 155
Figure 5.12. The case group’s constructed representations of chocolate at 10°C and 20°C................................................................. 156
Figure 5.13. The case group’s representations of particles in a conductor and an insulator................................................................. 161
Figure 5.14. Screenshots of the video Energy Transfer Through Conduction.... 162
Figure 5.15. The case group’s temperature graph for the Heating Investigation........................................................................................................... 166
Figure 5.16. Screenshots of the video Energy Transfer by Convection......... 170
Figure 5.17. Final screenshots of the video Energy Transfer by Convection.... 171
Figure 5.18. The case group’s list of the key points and their representations about convection................................................................. 172
Figure 5.19. The case group’s representations for convection currents around a candle................................................................. 175
Figure 5.20. The case group’s representations for convection currents in a hot water heater. ........................................................................................................... 176
Figure 5.21. Teabag rocket representations by Ina and Megan....................... 177
Figure 5.22. Example of the Key ideas and Ina’s questions about radiation. ..... 180
Figure 5.23. Screenshots of the video Energy Transfer by Radiation ............ 181
Figure 5.24. The case group’s representations comparing waves. .................. 183
Figure 5.25. Activity 8.3 Examples of the first two slides for Ina’s and Megan’s presentation. ................................................................. 185
Figure 5.26. Mind map for Clara and Anna. ................................................ 186
Figure 6.1. The Sustainable House Inquiry task, as presented in the online module........................................................................................................... 199
Figure 6.2. Clara demonstrated the how the light will shine down on the carton (left) and Ina used gestures to show how foil on the outside attracts heat (right).................................................................. 207
Figure 6.3. Ina’s project book showing the inquiry questions and predictions. .. 208
Figure 6.4. The case group engaged with different representations in Episode 2 (left) and Ina used gestures to explain an idea in Episode 3 (right). .............. 211
Figure 6.5. The case group’s set up of the first control trial (left) with the datalogger on the bottom right hand side of the photo (right).............................. 218
Figure 6.6. As Megan explained how heat bounced off the reflective surface as Ina gestured. ................................................................. 223

Figure 6.7. Graph generated by the datalogger showing a decrease (left side of graph) then an increase in temperature (right side of graph), with a close-up view (right). ................................................................. 231

Figure 6.8. Data tables by Ina (above) and Megan (below). ....................... 234

Figure 7.1. Ina’s pre-test (left) and post-test (right) responses to Q8 .............. 266

Figure 7.2. Ina’s pre-test (left) and post-test (right) responses to Q9 .............. 269

Figure 7.3. Ina’s pre-test (left) and post-test (right) responses to Q10 ............ 271

Figure 7.4. Megan’s pre-test (left) and post-test (right) responses to Q8 ........ 274

Figure 7.5. Megan’s pre-test (left) and post-test (right) responses to Q9 ........ 275

Figure 7.6. Megan’s pre-test (left) and post-test (right) responses to Q10 ......... 276

Figure 7.7. Clara’s pre-test (left) and post-test (right) responses to Q8 ............ 277

Figure 7.8. Clara’s pre-test (left) and post-test (right) responses to Q9 ............ 278

Figure 7.9. Clara’s pre-test (left) and post-test (right) responses to Q10 .......... 279

Figure 7.10. Two examples illustrating the range of classroom responses to Q10 .............................................................................................................. 282

Figure 7.11. Sequence of representational products and classroom processes in Ina’s Learning Pathway: Temperature and thermal energy (Module 5). .......... 289

Figure 7.12. Sequence of representational products and classroom processes in Ina’s Learning Pathway: Conduction (Module 6). ......................................................... 298

Figure 7.13. Sequence of representational products and classroom processes in Ina’s Learning Pathway: Convection (Module 7). .......................... 301

Figure 7.14. Sequence of representational products and classroom processes in Ina’s Learning Pathway: Radiation (Module 8). .......................... 306
### List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATSE</td>
<td>Australian Academy of Technology and Engineering</td>
</tr>
<tr>
<td>BLE</td>
<td>Blended Learning Environment</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
</tr>
<tr>
<td>DCog</td>
<td>Distributed Cognition</td>
</tr>
<tr>
<td>DLE</td>
<td>Digital Learning Environment</td>
</tr>
<tr>
<td>EGR</td>
<td>Expert Generated Representation</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communication Technology</td>
</tr>
<tr>
<td>MCQ</td>
<td>Multiple Choice Questions</td>
</tr>
<tr>
<td>MRC</td>
<td>Metarepresentational Competence</td>
</tr>
<tr>
<td>MYP</td>
<td>Middle Years Programme</td>
</tr>
<tr>
<td>PhET</td>
<td>Physics Education Technology</td>
</tr>
<tr>
<td>RC</td>
<td>Representational Competence</td>
</tr>
<tr>
<td>RCA</td>
<td>Representation Construction Approach</td>
</tr>
<tr>
<td>SGR</td>
<td>Student-generated Representation</td>
</tr>
<tr>
<td>SH</td>
<td>Sustainable Housing</td>
</tr>
<tr>
<td>STELR</td>
<td>Science and Technology Education Leveraging Relevance</td>
</tr>
<tr>
<td>STEM</td>
<td>Science, Technology, Engineering, Mathematics</td>
</tr>
<tr>
<td>STILE</td>
<td>Student Teacher Interactive Learning Platform</td>
</tr>
<tr>
<td>VCE</td>
<td>Victorian Certificate of Education</td>
</tr>
<tr>
<td>VET</td>
<td>Vocational Education and Training</td>
</tr>
<tr>
<td>VSRI</td>
<td>Video Stimulated Recall Interview</td>
</tr>
</tbody>
</table>
Abstract

Contemporary approaches to teaching and learning science involve students’ experience of authentic meaning-making processes based on scientific practices. These include the guided-inquiry Representation Construction Approach (RCA) where students generate, use, negotiate, and evaluate multimodal representations to explain their ideas, make claims, and solve problems. The RCA in non-digital classrooms has been shown to lead to deeper conceptual learning as a result of students engaging in these epistemic processes. This research is part of an Australian Research Council (ARC) Discovery project and focuses on how the application of RCA in a Digital Learning Environment (DLE) engages students in learning science. Specifically, it examines the features of the DLE and how they supported the generative design and sequencing of activities and processes for student conceptual and representational development.

Research for this investigation took place at an all-girls school in Melbourne, Australia. The research involved 27 Year 9 science students learning about energy transfer (i.e. physics) in the socio-scientific context of sustainable housing and climate change, based on the Australian national curriculum. The research design was informed by a distributed cognition theoretical framework and followed an ethnographic methodology with a case study approach. Both quantitative and qualitative data were generated through participant observation with video capture, video-based stimulated recall interviews, student-constructed representations, pre- and post-tests, and a questionnaire. Multiple theoretical frameworks were used to analyse the students’ responses.

The findings indicated the generative capability of the digital delivery for RCA. The DLE extended flexibility and access to multimodal semiotic resources
to support students’ meaning-making processes and their individual learning pathways. Generative digital features included the interactive online learning platform and the purpose-made videos to support representation-focused learning. The findings also indicated students’ conceptual learning was gradual and varied across the design and sequencing of representational resources provided in the learning environment. These patterns indicated that to support students’ conceptual and representational development, the design of the digital learning sequences needs to include: multiple cross-modal interactions, the timely provision of canonical resources, and the meaningful application of knowledge to new contexts. While the DLE supported student-to-student dialogue, recognised as central for the inquiry-based processes of RCA, specific opportunities to negotiate, evaluate, and refine students’ constructed representations were limited, impacting students’ overall learning gains. For the summative inquiry task, the DCog perspective indicated a gradual but generative transfer of knowledge through collaborative informal and formal reasoning processes across multimodal representational resources, reflective of an authentic scientific inquiry.

This research has led to guidelines for a generative digital design and sequencing of representational tasks and resources (e.g., online learning platforms), along with recommendations to support teachers to provide the formative processes that capture the critical features of the RCA. The findings also have implications for the design of curriculum and assessment, both at a policy and classroom level. The broader significance of this research relates to its applicability to improve the quality of student learning and engagement in science and STEM through a more meaningful integration of digital technologies with RCA and a stronger focus on real-world issues.
Chapter 1. Introduction

This thesis is part of Deakin University’s Australian Research Council (ARC) Discovery Project: “Developing digital pedagogies in inquiry science through a cloud-based teaching and learning environment” (i.e., ARC digital inquiry project). The aim of the project is to investigate science teaching and learning through the integration of a Representation Construction Approach (RCA) and digital technologies. My research focuses on the learning afforded through representation construction in a digital learning environment. It follows an ethnographic methodology using multiple data generation methods to understand how students learn and engage in this interactive setting. My findings support the ARC digital inquiry project and are of interest to educators and organisations looking for strategies to shift science teaching and learning towards an active knowledge construction process that more closely emulates that of scientific practice, within a contemporary digital learning environment.

This thesis is presented in nine chapters beginning with an introduction, literature view and methodology, followed by four chapters analysing the findings, a discussion chapter, and the conclusion. I begin by describing the background for this research, then introduce representation construction, outline the significance of the research, and present a synopsis of each chapter.

1.1 Background

Worldwide, governments have reported a consistent decline in student engagement with Science, Technology, Engineering, and Mathematics (STEM) during their transition from primary to secondary school (American Association for the Advancement of Science, 1989; European Commission, 2007; Freeman, Marginson, & Tytler, 2015; Harlen & Allende, 2009). Associated with this are...
growing concerns that graduates leave the education system with an inconsistent understanding of fundamental scientific concepts and limited awareness of the nature of scientific thinking (Tytler, 2007; Harlen & Bell, 2010). Moreover, the increased use of Information and communication technology (ICT) in science classrooms has not led to an improvement in learning outcomes (Organization for the Economic Co-operation of Development [OECD], 2015a). The decline in participation and quality learning in science paradoxically comes at a time when increasingly complex global issues and future technologically oriented labour markets demand a scientifically literate citizenry (Tytler, 2007). As a response, organisations are calling for a re-orientation of science education towards inquiry-based teaching and learning, more meaningful integration of digital technologies, development of scientific literacy, and a stronger focus on real-world issues (Duschl, Schweingruber, & Shouse, 2007; European Commission, 2007; Tytler, 2007). One approach, representation construction, has shown great promise in achieving these goals.

1.1.1 Representation construction pedagogy and digital technologies

Drawings and models have a long history in both science and science education as representations that act as approximations of reality (Ainsworth, Prain, & Tytler, 2011; Latour, 1990). Representations also include text, symbols, mathematical formulae, graphs, tables, photographs, digital images, gestures, and role-play (Waldrip & Prain, 2012). A fundamental part of scientific literacy is to be able to use representations to construct, coordinate, and communicate meaning (AAAS, 1989; Lemke, 2004; Tytler, Prain, & Hubber, 2018). In addition to the use of representations to portray already-resolved scientific facts and processes, there is growing evidence of their potential as tools for thinking and learning.
science (diSessa, 2004; Greeno & Hall, 1997; Klein, 2006). Instead of using already prepared or expert-generated representations, students create their own representations.

When students create their own representations or make choices about which representations best suit a given purpose, they become more actively engaged in their own learning (Ainsworth et al., 2011; Greeno & Hall, 1997; Prain & Tytler, 2012). Constructing their own representations enables students to make sense of ideas and concepts, solve problems, and develop understanding (diSessa, 2004). The visual nature of representations allows students to share their ideas with others for discussion and evaluation and enables teachers to assess students’ understanding and adapt instruction (Prain & Waldrip, 2010).

Constructing and critiquing representations enables students to build knowledge in much the same way as scientists, through a creative and collaborative process of refining ideas, reasoning, justifying, and evaluating their own claims or those of others (AAAS, 1989; Ainsworth et al., 2011; Tytler & Prain, 2012). As students become aware of the affordances and constraints of different representations, they learn to choose which ones better represent certain concepts, thereby developing their metacognitive skills (diSessa, 2004). Students develop a deeper understanding of fundamental scientific concepts, which builds strong foundations for future learning (Bransford, Brown, & Cockling, 2000; Tyler & Prain, 2010).

The success of student-generated representation construction relies in part on the teacher’s ability to develop and guide students through discussions and activities that challenge their thinking (Lehrer & Schauble, 2006; Waldrip, Prain, & Sellings, 2013b). Through open-ended questions and discussion (i.e., inquiry),
teachers draw on students’ curiosity, build on prior knowledge, and identify possible misconceptions. Teachers scaffold discussions and activities, focus students’ reasoning, and build class consensus while guiding them towards a more authorised scientific understanding (Hubber, Tytler, & Haslam, 2010; Tytler, Hubber, Prain, & Waldrip, 2013b). The combination of teacher-guided inquiry with representation construction is a powerful teaching and learning tool that has a basis in modern cognitive science (Klein, 2006). This approach contributes to quality learning and improved student engagement (Ainsworth et al., 2011; Tytler, Haslam, Prain, & Hubber, 2009).

The integration of digital technologies with student-generated representation construction is growing and has the potential to support quality science learning (Ainsworth et al., 2011; Lemke, 1998a; Osborne & Hennessy, 2003). Digital technologies add to the diversity of approaches for learning scientific concepts and processes (Tytler, Prain, & Peterson, 2007). My research focuses on a particular interactive cloud-based learning platform used to organise and deliver this active pedagogy.

1.2 Significance

The ARC digital inquiry project extends RCA into a digitally-rich learning environment. The project is part of a collaboration with two organisations, STELR and STILE. Australia’s Science and Technology Leveraging Relevance (STELR) program is a secondary school science education curriculum initiative developed by the Australian Academy of Technology and Engineering (ATSE) that explores renewable energies through contemporary technologies in an effort to address the low participation rates in science (Finkel, Pentland, Hubber, Blake, & Tytler, 2009). Building on previously successful initiatives combining inquiry-
based teaching with student-generated representation construction in science, STELR integrates digital technologies used in science to find solutions to real-world issues and to improve students’ understanding of fundamental concepts in science, while developing their scientific literacy skills and appreciation of the collaborative nature of science (Finkel et al., 2009).

The first STELR unit consisted of 10 lessons based around climate change and renewable energy. Student evaluations were positive and demonstrated increased student involvement and engagement in science classes, a stronger perception that science was relevant to their lives, and that learning science in school was important. Students identified the following attributes that supported their learning: the hands-on nature of the STELR activities, a shift away from textbooks, the use of digital technologies, opportunities to solve real-world problems, freedom to choose investigations and identify related problems, and increased participation in productive class discussions. In addition, students noticed less didactic teaching and perceived their teachers to be co-investigators in their inquiry. There is a growing network of STELR schools across Australia, including the one involved in this research project.

STILE Education is a partner organisation with STELR that has developed cloud-based teacher and learning software to support science units. The online platform called the Student-Teacher Interactive Learning Environment (STILE) was used to scaffold science lessons and resources from the STELR curriculum as part of the iSTELR project (see https://www.youtube.com/watch?v=FpG54gJWp3s to view a demonstration of iSTELR). The STILE platform enables educators to adapt, create, and use pre-existing or new curriculum and has the capacity to accommodate both digital and
non-digital student-generated representations. The chief investigators in the ARC digital inquiry project had been working with some iSTELR schools to adapt selected iSTELR modules to reflect RCA principles and approaches, along with the integration of a broad selection of digital technologies (e.g., laptops, dataloggers). The aims of the ARC digital inquiry project are to investigate to the potential of STILE to support RCA and the student learning outcomes; to identify pedagogical implications and challenges for teachers and students; and to investigate the use of digital technologies to support teacher learning in STILE.

Within the ARC digital inquiry project, my study focuses on students’ experience with this approach, though there was some natural overlap with the other research aims. Specifically, my research focus is to investigate how a digital learning environment designed with an inquiry-based representation approach engages students in learning science. Findings from my study have direct implications for the project by contributing the perspective of the students in understanding of the affordances of the digital technologies integrating this pedagogical approach. My findings have broader significance for educators interested in effective strategies to engage students in more active and authentic scientific practices with the productive integration of digital technologies in learning environments.

1.3 Structure of the Thesis

Chapter 1 introduces the research as part of the ARC digital inquiry project and situates it within the broader literature regarding the decline of students’ interest and engagement in learning science. In this chapter, I introduce the RCA to teaching and learning science and outline the results of the pilot study that featured this interactive pedagogy on an online learning platform. This
chapter also presents the research questions (RQ), which the remainder of this thesis is designed to address.

Chapter 2 elaborates on RCA and situates it within the context of science education and learning sciences literature. This chapter identifies the traditional approaches to and challenges of teaching science and highlights some of the contemporary perspectives on teaching and learning science. I elaborate on the philosophical and theoretical perspectives that inform RCA, including an account of the semiotic and epistemic perspectives inherent in the meaning-making processes that inform my analysis. I then review some of the challenges and possibilities of incorporating digital technologies to support science education. The ideas in this chapter lead to the justification for my research and I conclude with a full outline of my research focus including the four research questions.

Chapter 3 outlines the methodology for my research, focusing on the rationale for the research design, including the specific design features of the STILE-based unit. I begin by explaining how my methodology situates within the qualitative paradigm and draws on an ethnographic case study approach. I then introduce my theoretical framework of distributed cognition and explain how I used it to organise my data generation methods to gain a more comprehensive understanding of the dynamic social and material interactions in this digital learning environment. Finally, I elaborate on my data generation and analysis, data quality, my role as a participant researcher, and the ethical considerations for this naturalistic investigation.

Chapter 4 is the first of four chapters analysing the data and presenting the findings. It presents the unit as experienced by the students, elaborating on their face-to-face and online interactions, along with the social and material
interactions through video analysis. This chapter addresses RQ1: *What were the generative features of this Digital Learning Environment (DLE) in supporting an inquiry-based Representation-Construction Approach (RCA)*? I argue that this DLE provided flexibility for variations in students’ learning pathways, a high proportion of face-to-face interactions and student-to-student dialogue, and a broad range of representational resources for meaning-making processes. Chapter 4 provides the foundational context to all the research questions and a rich description of this DLE.

Chapter 5, the second findings chapter, provides a more in-depth analysis of the students’ experience of the unit through their responses. This chapter presents the detailed perspective of a case group and features their unique and varied responses to the activities across the modules, with comparisons to the whole class where possible. Chapter 5 also addresses RQ1, in addition to RQ4: *What are the implications for the design of digitally-based RCA units*? I argue that the DLE provided flexible and expanded delivery of representational resources though there were limitations in some of the key formative processes to support students’ learning outcomes.

Chapter 6 is the third findings chapter and focuses on the students’ experience of the sustainable house summative task. This task took place over three lessons and was the only formally assessed task in the unit. It was designed as a group-based guided-inquiry around the context of passive designs for sustainability and required students to apply their understanding of concepts related to energy transfer. It addresses RQ2: *How did the summative inquiry task support epistemic processes representative of scientific practice*? I argue that this summative task supported a genuine engagement in scientific inquiry, resulting in
students’ ability to apply their conceptual knowledge to provide an explanatory account of their results.

Chapter 7 is the fourth findings chapter, presenting an overview of students’ learning journeys across the unit, integrating the findings presented in the previous chapters. In this chapter, I analyse students’ responses to the pre- and post-test and explore their learning journey across the conceptually focused modules, connecting their responses to classroom processes. It addresses RQ3: *What were the patterns of conceptual and representational development in response to RCA in this digital environment?* I argue that students showed improved, though inconsistent conceptual understanding and representational competence, which related to their experiences with the representational resources in the learning sequences to support meaning-making processes.

Chapter 8 is the discussion chapter, which is divided into five sections addressing each of the four research questions and the overall research focus. In relating my findings to the literature, I outline the affordances of the digital learning environment for supporting students’ meaning-making processes through representation-focused approaches: I identify key generative features of this digital learning environment in supporting representation-focused approaches; the design considerations and potential for epistemically-rich inquiry tasks; the complexity of students’ learning and challenges for assessment practices; and the implications for designing generative learning sequences. Finally, I address the potential of representation-focused approaches in (re)engaging students in learning science, particularly those who have historically been excluded from this creative and interactive practice.
The final part of this thesis, Chapter 9, draws the key themes emerging from the discussion chapter to present the three main conclusions and related implications. I conclude by reflecting on my methodology along with future considerations for this research area.
Chapter 2. Literature Review

The focus of my research is to investigate how a digital learning environment designed with an inquiry-based representation construction approach engages students in learning science. To begin, I identify some of the traditional approaches and challenges of teaching science, highlight contemporary perspectives to teaching and learning science, and elaborate on the inquiry-based representational construction approach. I also review some of the challenges and possibilities of incorporating digital technologies to support science education. This chapter concludes with an outline of my research focus.

2.1 The Challenges of Teaching and Learning Science

Despite the rapid pace of societal changes, the mainstream approach to science education has remained largely unchanged since the 1950s (Harlen & Bell, 2010). Historically, the science curriculum has been organised into disciplinary strands (e.g., biology, chemistry, physics) covering a broad range of topics (Schweingruber, Keller, & Quinn, 2012). It has tended to overemphasise facts and skills (Duschl & Grandy, 2013) and remains largely irrelevant to everyday life (Johnstone, 1991). Classroom science investigations have been based on a single scientific method using procedurally-based activities and experiments with known outcomes (Osborne & Dillon, 2010; Hofstein & Lunetta, 2004; Schweingruber et al., 2012). Pedagogies have been based on authoritarian (Osborne & Henessey, 2003) and teacher-centred approaches, guided heavily by the textbook (Harlen & Bell, 2010; Lyons, 2006). Consequently, students generally associate science with memorising disconnected and irrelevant facts and terminology and as a single method for understanding the world (Lyons, 2006; AAAS, 1989; Schweingruber et al., 2012). The effect of this transmissive and
prescriptive approach, elements of which are still prevalent, is thought to contribute to students’ disengagement, their lack of understanding of the broader nature of scientific thinking, the persistence of scientific misconceptions, and an inability to understand how science relates to their lives (AAAS, 1989; Harlen & Bell, 2010; Lyons, 2006).

2.1.1 Why is learning science challenging?

Science encompasses a vast, growing, and dynamic body of knowledge and exploration, with the range of discovery spanning very small to very large dimensions. These often extend beyond students’ direct experiences or the abilities of their senses to observe without the aid of technology. Whereas some objects and processes are readily observed with the naked eye (e.g., trees, the sun rising and setting), observing and explaining microscopic and submicroscopic processes require sophisticated technology or highly symbolic forms of explanations (e.g., photosynthesis, the day and night cycle) (Gilbert, 2008; Johnstone, 1991; Tasker & Dalton, 2008). The associated conceptual and symbolic dimensions of science require students to think on multiple levels and are thought to be the central challenge of learning science (Gilbert, 2008; Tasker & Dalton, 2008).

Although observations have an important role in science, the reliance on observations limits the explanatory potential of science (Osborne & Dillon, 2010). Researchers argue that students live perfectly well in the observable world and may find it challenging or counter-intuitive to relate to or understand the less observable dimensions (Gilbert, 2008; Johnstone, 1991; Tasker & Dalton, 2008). Further, in relating these levels, instruction typically involves multiple representations to convey ideas and can rapidly switch between abstracted
symbols and the real phenomena (Lemke, 2002). This inherently multimodal nature of science requires students to interpret and relate these representations to reality, which places additional demands on them (Ainsworth, 2014; Lemke, 2002). The overemphasis on transmissive forms of instruction promoting difficult terminology, abstracted ideas, and multimodal representations makes science particularly challenging for students. It encourages the memorization of facts and processes and does not promote an understanding of the active nature of knowledge construction and change inherent in scientific practices (Tytler & Prain, 2013a).

2.1.2 Learning scientific concepts

One of the early and important shifts from transmissive approaches to teaching and learning science was conceptual change theory (Duschl & Grandy, 2013). The idea of conceptual change originated with Kuhn’s (1996) metaphor for paradigm change in science, which involves the replacement of old theories when there is enough new evidence to challenge current ideas. Students come to science class with their own intuitive or pre-conceived ideas of how the physical world works, ideas which are consistent across cultures and often conflict with the scientific explanation of the world (Duit & Treagust, 2003; Duschl & Grandy, 2013; Taber, 2013). Conceptual change approaches aim to shift student’s intuitive ideas towards a more scientific view (Duit & Treagust, 2003). Following Kuhn (1996), classical conceptual change posits a similar rational process of naïve theory replacement based on students’ dissatisfaction with their current ideas and an understanding that newer ideas are more plausible and have higher explanatory power (Duit & Treagust, 2012; Posner, Strike, Hewson, & Gertzog, 1982; Vosniadou, 2008). The change involves individual and internal processes of
learning, where concepts are understood as resolved linguistic entities and as the drivers for learning (Klein, 2006; Tytler & Prain, 2013a). Although challenging students’ prior knowledge has been shown to be necessary for conceptual change, an overemphasis on individual learning, content knowledge over process, observations over other ways of knowing, and the use of complex or abstract models has resulted in students often reverting to their misconceptions in new contexts, or developing a hybrid of their old and new thinking (Tytler & Prain, 2013a; Duit & Treagust, 2003). More recent developments in science education research have identified important cognitive, social, and epistemic practices for the teaching and learning of science (Duit & Treagust, 2012; Duschl & Grandy, 2013), along with specific roles for language, tools, and context for supporting learning processes (Klein, 2006; Tytler & Prain, 2013a).

2.1.3 Contemporary perspectives on learning

Contemporary cognitive science views the brain and learning as adaptive, networked, perceptual, analogous, and metaphorical; where learning orients around big ideas, patterns, relationships, and deep conceptual understanding and is strongly influenced by context, perception, and emotion (Bransford et al., 2000; Klein, 2006). These contemporary views contrast with the so-called first generation cognitive science, which regards thinking as an isolated process in the mind, where individuals manipulate concepts and propositions through deductive logic and rules in a manner similar to a computer processor (Klein, 2006). The second generation cognitive science emphasises a greater role for agency and processes and views discursive practices inclusive of actions and interactions within a cultural context as essential to learning (Harré, 2002).
Although formal reasoning processes (e.g., deductive logic, linguistic approaches) have a role in science, informal processes (e.g., creativity, intuition, metaphors) are integral to scientific inquiry, particularly in the initial exploratory phase. Informal reasoning processes have therefore been taken up by advocates of representational approaches for students to engage in meaning-making processes (Tytler, Prain, Hubber, & Haslam, 2013c).

The role of context involves an interplay of place, practices, and tools, relating more broadly to socio-cultural and epistemic perspectives. Learning linked to context and cultural practices includes tools and ways of representing and communicating ideas (Duschl & Grandy, 2013). Socio-cultural perspectives follow Vygotsky’s (1962, 1978) research indicating the social role of learning; particularly, the role of language and other symbolic tools for joint meaning making. Second generation cognitive science considers that language interacts with thought, as an analogous, metaphorical narrative, as opposed to simply being a by-product of thought (Klein, 2006). Consequently, in science education, the role of discourse becomes critical to bridging the gap between everyday language and scientifically authorised knowledge (Klein, 2006). Related, are the broader epistemic knowledge-building practices of science as a discipline (Greeno & Hall, 1997; Prain & Tytler, 2012), where practical activities make use of cultural conventions and tools as a social endeavor (Driver, Asoko, Leach, & Scott, 1994; Mercer, 2004; Mercer, Dawes, Wegerif, & Sams, 2004a). Both socio-cultural and epistemic perspectives underpin the representation construction approach and are addressed in more detail in the following section.

Contemporary views in cognition address the role of context and culture with theories of distributed cognition, situated cognition, and embodied cognition,
which inform different aspects of my research. Although the broader field of grounded cognition is still evolving (Barsalou, 2008), these three theories situate within a socio-cultural perspective and extend the notion of cognition beyond the individual mind, emphasising different aspects of the social and material context.

Situative theory emphasises the role of social context for learning, with a specific set of practices in a given community (Greeno, 1998; Lave & Wegner, 1991). This theory links knowing and doing as embedded practices within activities, context and culture, where learning is a social and emergent process (Browns, Collins, & Duguid, 1989). Related to this theory is the idea of affordances, where features of the environment prompt or support an action (Gibson, 1979). Affordances can either enable or constrain an action. Situated actions are thus the interplay of actions in a given environment, influencing cognition (Barsolou, 2008). Situated theory underpins a key analytic framework I used to assess students’ learning (see Chapter 7) and emphasises the disciplinary practice in the construction and use of representations. In addition, I relate affordances to the tasks and modes in which students construct representations as part of the meaning-making process.

Distributed Cognition (DCog) extends individual learning to the social and material contexts. DCog involves the distribution of cognition across people and resources as they undertake a task (Hutchins, 1995, 2014; Zhang & Patel, 2006). Within a given cultural-cognitive ecosystem (Hutchins, 2010), cognition is active and enactive, where the resulting emergent behaviours are distinct and more substantial than their constituent parts (Hutchins, 1995; Pea, 1993; Zhang & Patel, 2006). The development of new practices is constrained by the social and material interactions within any dynamic and adaptive ecosystem (Hutchins, 2010, 2014);
hence are important considerations in the design of tasks and provision of resources in the science classroom. DCog articulates the relationship between the process of meaning making with representational resources. In doing so, it extends the socio-cultural perspective in relation to a given learning environment. DCog provides insights to my investigation, particularly with the summative inquiry task which involves interactions among students with one another and with a variety of forms of technology which actively frame the learning, and for this reason is one of the main theoretical perspectives in my study.

Finally, embodied perspectives connect sensorimotor and cognitive processes such that body-based representations (e.g., role-plays, gestures) can be mapped to abstract concepts to promote analogical reasoning (Weisberg & Newcombe, 2017). Although cognitive processes can take place independently of the body (Barsalou, 2008), these forms of representation ground actions to thoughts and provide a direct and possibly more powerful link to abstract ideas (Goldin-Meadow & Beilock, 2010). The role of embodied cognition has implications for the learning associated with the use of body-based representations in my study.

Extending these theories is the idea that cognition is inextricably coupled with our material environment (e.g., symbols, tools, techniques) as a continuously active and enactive process (Hutchins, 2010; Maturana & Varela, 1992; Malafouris, 2013). Ideas such as *structural coupling* (Maturana & Varela, 1992) and Material Engagement Theory (MET) (Malafouris, 2013) view our brains, body, and environment as co-evolved, where ongoing interactions bring forth our world, resulting in cultural and biological evolution as synchronous processes. These views contrast with the individual and computational view of how the mind
works and extend the socio-cultural and socio-semiotic perspectives. Where Vygotsky proposes the role of material culture in mediating thought, MET indicates it is coupled with thought, enacting a world and emergent thinking. Where Pierce (1955, 1998) indicates the role of signs for meaning making, MET views the signs as enactive semiotic processes, influencing our perceived reality and emphasising the interaction between intention and affordance (Malafouris, 2013). These enactive perspectives are consistent with the more contemporary interpretations of DCog (Hutchins 2010, 2014) and are central in research relating to human and computer interactions, offering theoretical frameworks for the design of learning technologies with implications for future research in this area.

In summary, contemporary views in cognitive theory extend traditional views of learning, presenting both challenges and opportunities for teaching and learning science. The next section focuses on the language of science, providing insight into the complexities of the scientific endeavour and how this translates into the classroom.

2.1.4 The multimodal language of science

Traditional science classes have typically relied on spoken and written modes of communication; this contrasts with the fundamentally multimodal nature of science where meaning making occurs through activities that integrate text, dialogue, mathematical formulas, visual representations, and apparatus (Lemke, 2004). According to the multimodal view of science, concepts are not static facts or written definitions, but linked ideas and practices within a disciplinary context (Taber, 2013). Concepts are thus the sum of the representations that describe them (Lemke, 1998b). Therefore, in emulating the practices of modern science, students need to construct, coordinate, and interpret
multiple representations and modes to learn science (Lemke, 1998c; Tytler et al., 2013b).

Although the terms *modes* and *representations* are sometimes used synonymously in the literature, in my study I have identified specific modes (i.e., verbal, written, visual, actions) within which multiple representational forms can be organised (e.g., dialogue, written text, drawings, role-plays); however, what constitutes a mode may vary in different contexts (Bezem & Kress, 2016).

Social semiotic multimodal theory explains how learning takes place: each mode is considered part of a meaning-making system, where meaning is distributed across modes, though not necessarily evenly (Bezem & Kress, 2016). When combined, multimodal representations convey meaning, with each mode offering partial access to the meaning. Each mode is potentially important for meaning making and communication though certain modes may be better suited to certain situations. Thus, meaning is constructed using the resources provided in a given environment and through specific social interactions (Bezem & Kress, 2016; diSessa & Sherin, 2000).

The ability to coordinate more than one representation with a given mode or across modes is also fundamental to learning science (Ainsworth, 2008; diSessa, 2004). Building on students’ “deep, rich, and generative” understanding of representations (diSessa & Sherin, 2000, p. 387) and having them construct their own representations provides powerful affordances for learning (Ainsworth et al., 2011). During the process of representing and re-representing ideas in different forms, students must decide what aspects to represent and how to best to represent them (Karmiloff-Smith, 1992). This process engages students in a learning strategy that is visually and spatially distinct from reading and writing.
(Ainsworth et al., 2011). The process of constructing, using, and relating representations also places additional learning demands on students (Ainsworth, 2014; Lemke, 2002).

In describing students’ ability to construct and use representations, two important approaches are central to my research. DiSessa (2004) described the ability to develop, explain, and compare representations, as well as to understand their purpose, application, and limits as metarepresentational competence (MRC). He identified elementary and secondary students’ natural abilities in drawing as well as representing ideas in relation to time (i.e., temporal ideas). He also noticed students were attuned to perceptual attributes such as colour, and exhibited critical capabilities in appreciating specific attributes in representations (e.g., completeness, accuracy, simplicity, conventionality). Students’ patterns of development indicated their initial representations tended to be more realistic and contain more information than necessary; later on, they were able to develop more abstract and systematic representations. DiSessa (2004) concluded students were able to develop quality representations, and with instruction, learn how to modify and combine them in a more scientifically consistent manner.

In contrast to the student-focused orientation of MRC, Kozma and Russell (2005) developed a framework of representational competence (RC) based around how chemists and undergraduate chemistry students used representations. They described RC as a set of skills and practices which enable the reflective use of representations to help think about, communicate, and act on observable and non-observable chemical processes. Their study design was informed by situative theory (see Greeno, 1998), aligning with the nature of scientific practice, and the Multimedia Theory of Learning (see Mayer, 2001), reflecting the impact of
written and visual modes. Kozma and Russell (2005) organised their framework by patterns of development, from levels 1-5, in line with the Vygotskian “zone of proximal development” and accounting for the types of material and social resources available (p. 132). Their flexible use of their framework allowed for variation in a given students’ representations, which might be attributed to the influence of the instructional style, the representational resources available, and students' facility with the tools to access and create representations. Though both MRC and RC describe aspects of students’ ability to construct and use representations, I have incorporated Kozma and Russell’s (2005) RC framework into my analysis of students’ representations because it is situated in epistemic practices.

In addition to placing more demands on students, teaching through representations also places additional demands on teachers. Teachers need to understand what capabilities learners already have and guide them through a process of revision and refinement of their representations toward scientifically sophisticated representations (diSessa, 2004). The teacher must also be prepared to respond flexibly to a wide range of students’ representations and ideas, guide them in understanding their form and function in relation to specific tasks, and identify productive pathways for development (diSessa & Sherin, 2000).

In summary, contemporary views of learning encompass the role of formal and informal reasoning processes, context, and the multimodal nature of science. Central to these views is the shift of knowledge from a focus on outcomes to an interactive process (Bruner, 1971). For the teaching and learning of science, students need to have a more active role in knowledge generation and communication (McDermott, 2016). This includes experiences with the epistemic
processes of construction of arguments, theories, and models using the languages of science (Duschl et al., 2007), along with the continuous collaborative revision of ideas and the integration of and interaction with new technologies (Duschl & Grandy, 2013). These developments have implications for the structure, assessment, and delivery of science education (Yore, 2012). RCA is built upon many of these contemporary perspectives, offering a strategy by which students can actively engage in meaning-making processes through inquiry in a manner that is more consistent with scientific practice.

2.2 Inquiry-Based Representation Construction

Earlier, I described RCA as the guided process of students constructing, relating, and refining their own representations of a phenomenon. Through guided discussion and negotiation, these Student-Generated Representations (SGRs) become progressively more reflective of scientifically accepted understanding (Waldrip et al., 2013b; Tytler et al., 2013b). This section elaborates on the key philosophical and theoretical underpinnings of RCA, multimodality, and the inquiry-based nature of this pedagogy.

2.2.1 Philosophical and theoretical underpinnings of RCA

My investigation has its foundations in a strand of ongoing classroom-based research in Australia. The research involved the development, application, and refinement of science teaching practices culminating in RCA (Waldrip, Prain, & Carolan, 2010; Tytler et al., 2013b). RCA is informed by social constructivist, socio-cultural, and socio-semiotic perspectives, which link the discursive and disciplinary practices of science by engaging the affective, contextual, and metacognitive skills identified by contemporary cognitive science.
Constructivism is a central theory of learning initially described by Piaget (1952) as the process of students’ active integration of their prior knowledge and experiences with the new knowledge they learn in science classrooms (diSessa, 2006; Prain & Tytler, 2012; Taber, 2013). Identifying students’ prior knowledge is an important part of the conceptual change process (Bransford et al., 2000; diSessa, 2006) and also plays an important role in RCA (Waldrip et al., 2010; Tytler et al., 2013b). The limitation of constructivism is its focus on individual student learning (e.g., outside of social or cultural contexts) (Tytler & Prain, 2012; Vygotsky, 1978). Consideration of the role of context and perception in learning extends this central learning theory to align with social constructivist and socio-cultural perspectives (Tytler & Prain, 2012; Klein, 2006).

Tytler and Prain (2012) described social constructivism as the learning processes that take place as teachers and students co-construct knowledge. This perspective acknowledges the role of language, affect (e.g., attitudes, interest, feelings, motivation), and culture (e.g., scientific practices and ways of knowing) in learning. The teacher’s role is to create a learning environment where students engage in discussions about their ideas, and feel confident to share, justify, and communicate their learning. Socio-cultural perspectives consider the role of culture in learning; specifically, how classroom interactions are linked to the disciplinary or epistemic practices of science. Following Vygotsky (1962, 1978), language and tools mediate learning in science (Tytler & Prain, 2012). Authentic learning takes place when teachers and students interact through the languages and practices that develop, justify, and communicate knowledge in a manner similar to the disciplinary norms of science (Prain & Tytler, 2013).
From the socio-semiotic perspective, meaning making is social, material, and semiotic (Lemke, 2002), integrating the social role of learning with culturally specific meaning-making systems and practices. As a discipline, science uses a distinct language system involving multiple modes of representations to construct and convey meaning (see next section). Thus, students need to understand the language of science and be able to coordinate multimodal representations to participate in these communal epistemic practices.

Where socio-semiotic perspectives encompass the social and cultural aspect of learning, semiotics focuses solely on the use of signs. Peirce’s (1955, 1998) philosophy of semiotics is central to RCA. Semiotics is the study of signs (e.g., words, pictures, gestures). Signs are representations that convey meaning, require interpretation, and enable people to make sense of the world. Peirce (1955, 1998) developed a model for meaning making which relates the real-world referent (e.g., object, concept, phenomenon, experience), its representation (e.g., text, diagram, symbol, gesture), and how people make sense of it (e.g., meaning, idea, explanation). For example, drawing on Tytler et al.’s (2007) study of students learning about evaporation: the referent or the phenomena is changes to states of matter, its representation is a verbal explanation and/or a diagram of the process of evaporation, and the meaning (i.e., concept) is the idea of evaporation. This triadic relationship indicates that representations play a critical role in this meaning-making process (Tytler et al., 2013c). Thus, meaning in science is always representational (Prain & Tytler, 2013) and learning becomes a representational issue involving the development of students’ representational resources (Hubber et al., 2010).
2.2.2 Learning through different modes and multiple representations

In RCA, students engage, coordinate, and evaluate a variety of representations of phenomena across different representational forms and modes. Learning takes place through translation across representational forms and modes, and the conversations and activities around this process (Waldrip et al., 2013b). Through the negotiation of the modal affordances of their representations, students develop a deeper conceptual understanding (Tytler et al., 2007; Tytler & Prain, 2012). As students explore a given phenomenon and decide which representations best explain it, they engage in the meaning-making processes indicated in the Triadic Model. This is reflective of the epistemological dimension of learning where students develop an awareness of knowledge-building processes and deeper conceptual understanding (Tytler & Prain, 2013a). Further, students’ increasing refinement of representations (e.g., images, symbols) across multiple modes for the purposes of evaluation and communication is more reflective of scientific practice (Latour, 1990). Tytler, Peterson, and Prain (2006) argued that, “constructing and refining representations is a core knowledge construction activity within science and should therefore be a major emphasis in the science classroom” (p. 17). To do this, teachers need to structure learning sequences to support this level of engagement.

2.2.3 The role of inquiry in RCA

Inquiry-based science teaching has long been advocated to support authentic learning and improve student engagement in science (Harlen & Allende, 2009; Tytler, 2007; Furtak, Seidel, Iverson, & Briggs, 2012). Inquiry is an open approach to exploration, where students learn by collecting and using evidence, and engage in activities to test ways of explaining the phenomena under study.
Throughout this process, students draw on direct experience, refer to resources (including experts), and engage in discussions and debates to develop reasoning skills (Harlen & Allende, 2009). This iterative process is more reflective of how science is actually practiced, drawing on the provisional and collaborative nature of knowledge, and justification through evidence-based reasoning (AAAS, 1989; Schweingruber et al., 2012). In general, the teacher directs the inquiry through a series of open-ended questions and class discussions, scaffolding the process of exploration (Harlen & Allende, 2009; Hubber, 2014). Furtak et al. (2012) describe inquiry-based teaching “as part of a continuum of guidance” (p. 306) of teacher-led and student-led activities. The inquiry-based approach challenges the more transmissive methods that view science exploration as a single method. Students who learn through inquiry exhibit greater depth of understanding of concepts, are more actively engaged in their learning, and have a more positive attitude toward science (Harlen & Allende, 2009; Furtak et al., 2012).

A guided inquiry for RCA involves the teacher guiding students through the process of constructing, negotiating, and refining representations (Waldrip et al., 2013b). In contrast to the transmissive approach, teachers scaffold discussions and activities, through a series of representation challenges, to engage students in the epistemic process of scientific knowledge development and meaning making (Hubber et al., 2010; Prain & Tytler, 2013). During this process, the teacher identifies students’ understanding through their representations and provides nuanced feedback and guidance on the adequacy of students’ claims in relation to their representations (Waldrip et al., 2013b), modeling open and exploratory language (Hubber et al., 2010). This guidance is provided through the
sequencing of activities and ongoing feedback through discussions, gradually moving towards scientific understanding (Waldrip et al., 2013b). Using this inquiry-based approach requires more skill on the part of the teacher, takes more time in class and as a result, covers less content, but results in students’ gaining a deeper conceptual understanding of science (Hubber et al., 2010). The development of frameworks and principles to describe this guided and nuanced approach was integral to the design and delivery of RCA in my study.

2.2.4 The framework and principles of RCA

Waldrip et al. (2010) drew on their three-year longitudinal project as a basis for developing the IF-SO framework to guide the design of learning sequences based on RCA. The framework begins with teachers identifying (I) key concepts for the unit and developing a sequence (S) of representational challenges and tasks with close attention to the affordances and limitations of representations through their form and function (F). The sequence of student-generated representation should include those of interest to the students, appeal to their affective domain, and allow students to represent and re-represent their ideas. Throughout, the teacher provides ongoing assessment (O) opportunities for negotiation, and timely comparisons to canonical representations (Waldrip et al., 2010)

Tytler et al., (2013b) built on the IF-SO framework to develop the Principles Underpinning a Representation Construction Approach to Teaching and Learning. The Principles were developed through additional classroom-based research, providing a more elaborate account of learning processes in RCA. These principles are organised by four key interactions: design and delivery of the teaching sequences, discussion, meaningful learning through perceptual mapping,
and ongoing assessment. The teaching sequences are based on key concepts organised around key representational forms. Students engage in cross-modal coordination of their SGRs as the teacher facilitates the interplay with scientifically authorised information or appropriate Expert Generated Representations (EGRs), challenging students to refine and re-represent their ideas towards a canonical understanding. This interplay takes place through negotiation, where the teacher facilitates ongoing discussion with students about the purpose, form and function, and adequacy of their SGRs. In response, students compare and critique their own and other’s representation, with the guidance by their teacher, seeking consensus and shifting towards a more canonical understanding. Through meaningful contexts (e.g., everyday scenarios, hands-on activities) there is also constant two-way mapping where students are guided to relate the observable phenomenon to their SGRs. Embedded throughout this process is ongoing formative assessment through dialogue and tasks, focusing on the adequacy of SGRs and how students use them to explain phenomenon. Through RCA, students learn to construct, use, and interpret a variety of representations (e.g., text, drawings, gestures) to explain phenomena and solve meaningful problems. “Thus, understanding involves learning to generate and use representations to analyse and communicate a science idea, rather than learning either a concept or a representation as an end in itself” (Hubber et al., 2010, p. 8).

In summary, this section has elaborated on RCA, beginning with the philosophical and theoretical perspectives, the multimodal nature of developing disciplinary-based conceptual understanding, and the guided-inquiry approach underpinning RCA pedagogy. RCA provides a systematic way to transition the
teaching and learning of science from the acquisition of knowledge to a process of developing knowledge (Tytler & Prain, 2012).

As classrooms adopt more and diverse technologies, representations become increasingly digital in nature, calling for a need to explore the productive use of digital technologies for representation construction. My research focused on a classroom in which inquiry-based representation construction was incorporated with digital technologies. The research explored student learning and engagement, along with the affordances and constraints of different digital technologies. The final section of this literature review highlights the challenges and possibilities of using digital technologies for RCA, with a focus on online learning platforms.

2.3 Digital Learning

This final section begins with a broad outline of ICT in educational settings, with a focus on the Australian context. I then introduce digital learning environments and provide examples of how digital technologies have been used to support learning in science education. In keeping with the rapidly changing nature of digital learning, this section of the literature review draws from research between 2010–2018 with a focus on K-12 settings, but include some seminal papers that lie outside this range. The review also uses language in the following ways: the terms ICT and digital technologies include a broad range of software and the digital devices (e.g., desktop computers, laptop computers, tablets, iPads, digital loggers, interactive whiteboards, smartphones) that people use to access and communicate information (OECD, 2014; European Commission, 2013; Speak Up, 2015).
2.3.1 *Global trends and opportunities*

The two biggest trends worldwide are classroom access to the internet and student access to digital technologies. Most schools in developed countries have access to broadband, but with persistent disparities evident in the quality of connectivity and engagement between different student groups (e.g., socio-economic status, gender) (Freeman, Adams Becker, Cummins, Davis, & Giesinger, 2017; OECD, 2015a). Worldwide, most students now have access to computers both at school and at home, use computers more at home for schoolwork than at school, and are familiar with software that supports internet and digital communications (OECD, 2015a; European Commission, 2013). Of the OECD countries, Australia has among the greatest integration of ICT in schools—with each student having individual access to a computer at school, and one of the highest rates of student access to school laptops (OECD, 2015a). Australian students spend approximately one hour online each day at school, more than twice the OECD average, with almost half of that time used for school-related internet browsing (OECD, 2015a).

The integration of ICT in education settings supports contemporary pedagogical and assessment approaches, with the promise of greater access for all students. Examples include personalised learning that allows students to learn specific content at their own pace as well as to monitor their learning through real-time assessment (e.g., online video instruction, flipped classroom, online courses, use of learning analytics) (Patrick, Kennedy, & Powell, 2013; OECD, 2015a); and active learning approaches (e.g., problem-based learning, project-based learning, inquiry-based learning), which focus on authentic and student-centred activities (Freeman et al., 2017).
Science-specific examples include the digital scaffolding of guided learning through inquiry-based pedagogies (Longo, 2016; Srisawasdi & Panjaburee, 2016; Singa, Rogat, Adams-Wiggans, & Hmelo-Silver, 2015) and web-based adaptive learning (She & Liao, 2010; Srisawasdi & Panjaburee, 2016), along with the integration of digital tools (e.g., simulations, virtual labs, gaming software) (OECD, 2015a). Access to communications technology and social media connects students and teachers with peers and mentors in other classrooms, schools, districts and sectors, enabling a larger and more collaborative learning community (Wise & Schwartz, 2017) and potentially better access for students learning from home or in remote or disadvantaged situations (OECD, 2015a; Speak Up, 2015).

Despite the promise and use of ICT, there has been no appreciable learning gain in core learning areas in jurisdictions that have invested heavily in ICT for education (OECD, 2015a). Key issues relate to the ability of and support for students and teachers, as well as the design and application of ICT. For students, the myth of the digital native comes out of their ability to quickly adapt to digital technologies, not in how best to apply these skills to learning (Kirschner & De Bruyckere, 2017). Moreover, students are not a homogenous group of digital learners: there are significant differences within the same generation due to gender and socio-economic status (Freeman et al., 2017; Levy & Rowan, 2011; OECD, 2015a).

Meaningful integration of ICT requires evidence-based teaching pedagogies, robust and accessible digital technologies, and specific learning goals aimed at teacher training, resources, and curriculum (OECD, 2015a; Srisawasdi & Panjaburee, 2016). Teachers play a critical role in designing learning to
appropriately integrate technology with pedagogy and content, while supporting students with varying degrees of proficiency (OECD, 2012; Koehler & Mishra, 2009). More research is needed, however, to show that digital technologies improve learning to identify what works in the classroom (European Commission, 2013; Ifenthaler, 2017; OECD, 2014a).

Given the high level of access to and use of computers at school and at home in Australia, the call for effective design and implementation of digital learning environments is especially pertinent to my research. Understanding students’ use of digital technologies and the quality of the learning outcomes, particularly in relation to the online learning platform used in my study, will contribute to the design of learning environments and innovations that support learning processes (Ifenthaler, 2017; OECD, 2012).

### 2.3.2 Digital learning environments

As a broad category, DLEs include any set of technology-based methods that can be applied to support learning and instruction (Ifenthaler, 2017; Veletsianos, 2016; Wheeler, 2012). As a “constellation of technologies and spaces”, DLEs support interactions among teachers, students, and content in open- and closed-group or organisational settings (Veletsianos, 2016, p. 248). These technologies include computer-based learning systems where computers are used for instructional purposes (e.g., online learning, learning management systems, web-based adaptive systems), computer simulations, digital games, virtual reality, smartphone applications (Srisawasdi & Panjaburee, 2016), and a range of other digital technologies (e.g., animations, simulations, data probes) (Tasker & Dalton, 2006; Wise & Schwartz, 2017). Online learning platforms, videos, and dataloggers featured prominently in my research setting.
With initial beginnings in the tradition of distance learning (Means, Toyama, Murphy, Bakia, & Jones, 2009), the advent of digital technologies presents opportunities for pedagogies quite distinct from those available in conventional face-to-face classroom settings. These include remote accessibility to content and instruction anytime, from anywhere (Patrick et al., 2013; Means et al., 2009), expanded learning time for students (Means et al., 2009), access to digital media resources (She & Liao, 2010), along with synchronous and asynchronous communication and collaboration (Patrick, et al., 2013). The overall learning experience enables more learner control over many of these properties (Wise & Schwartz, 2017).

Early online learning environments tended to organise and deliver static content along with closed-ended tasks (Panjaburee & Srisawasdi, 2016; Richards & Dede, 2012; Richards & Walters, 2012), and often resulted in mixed improvements in learning (Barbour, 2014, Panjaburee & Srisawasdi, 2016). Contemporary approaches to digital learning call for evidence-based design, pedagogy, and application of technologies to support quality learning (Bransford et al., 2000; Veletsianos, 2016). These include dynamic designs based on more open and active-learning pedagogies, including inquiry, problem- and project-based learning (Freeman et al., 2017; Quintana, Reiser, Davis, Krajcik, Fretz, & Duncan 2004; Veletsianos, 2016), as well as adaptive learning customised to students learning progressions (She & Liao, 2010; Srisawasdi & Panjaburee, 2016). In the past decade, such collaborative digital pedagogies have been increasingly implemented in many educational settings (Wu & Wang, 2016) and are particularly relevant for learning science.
Online learning platforms require consideration of the inter-relationship among teacher-students-platform as a socio-cultural knowledge building construct (Richards & Walters, 2012). These learning systems are designed to support teacher-led classrooms with 1:1 hardware, and act as the primary carrier of curriculum, content, activities and assessment, accommodating open-ended responses, along with large and small group work (Richards & Dede, 2012). However, the implementation of these interactive systems requires a specific role for teachers in orchestrating the online and face-to-face activities as a blended experience.

**Blended learning environments**

The term Blended Learning Environment (BLE) has emerged in the literature to describe learning innovations which integrate technology-rich learning environments with more conventional media and different modes of instruction, such as whole-class or small group instruction (Horn & Fisher, 2017). Students exercise a degree of agency over their learning by accessing resources and tasks online (Barbour, 2014; Christensen, Horn, & Staker; 2013; Garrison & Vaughan, 2008; International Association for K-12 Online Learning [iNACOL], 2011). Although the definition of BLEs is evolving (Horn & Fisher, 2017), key features include a student-centred focus based on flexible and effective teaching and learning approaches, across both face-to-face and online domains, presented as a cohesive and integrated learning experience to support student learning outcomes (Bidarra & Rusman, 2017; Horn & Fisher, 2017; Patrick et al., 2013).

In contrast to a one size fits all approach, where all students progress at the same time through the same curriculum, there are a number of benefits and challenges associated with BLEs. Perhaps the most cited involves the shift toward
student-centred learning which provides greater student control and flexibility in pathways for their learning, how they demonstrate their understanding, as well as more flexibility in the pacing and context of learning (Bidarra & Rusman, 2017; Horn & Fisher, 2017; Patrick et al., 2013). Through the integration of digital technologies, BLEs have the potential to support a high level of differentiation of scale (Bidarra & Rusman, 2017; Horn & Fisher, 2017). This has been shown to increase student engagement, particular for at-risk students (Kyei-Blankson, & Ntuli, 2014) and those with a lack of interest in science and STEM (Craciun & Bunoiu, 2015). With access to resources from both domains, there is also potential to make better use of any ICT available in classroom settings and homes (Craciun & Bunoiu, 2015).

There are a variety of models to describe the nature of a BLE. Broadly, Blended Learning (BL) positions face-to-face and online learning along a continuum, with degrees of teacher-direction and online participation (Christensen et al., 2013; iNACOL, 2011). One typology has organised programs into four models around location, modality, and degree of teacher direction (Horn & Staker, 2014). In over 400 BL schools in the US, the Station Rotation model, where students rotate through the same stations in the classroom, is the most prevalent, especially in elementary schools (Horn & Fisher, 2017). This model supports student feedback, targeted instruction, student ownership of learning, quality peer-to-peer interactions, with different options for pacing and flexibility. With a strong focus on subjects, high-schools tend to offer the Flex model, which provides a self-paced approach for students and teacher-assistance as needed (Horn & Fisher, 2017). The design principles address four main areas: students’ agency, along with the effective use of technology, pedagogy, and assessment.
The integration of face-to-face and online components addresses the needs and preferences of students. The use of technologies supports effective and interactive pedagogies along with an ongoing assessment of students’ learning. Though these broad insights are useful in understanding the possibilities opened up in a BLE, they offer little insight into how to support complex disciplinary practice in subjects such as science. The arguments for blended learning in science centre around the need to improve student engagement through the integration of contemporary disciplinary-specific approaches using ICT (Bidarra & Rusman, 2017; Craciun & Bunoiu, 2015; Longo, 2016). Using the classification of Horn and Staker (2014), Craciun and Bunoiu (2015) proposed the Rotation models (e.g., station, lab, flipped) and the Flex model best suited secondary education, given the resources currently in place. Craciun and Bunoiu (2015) argued that these two models best supported discipline-based practices such as scientific investigations, problem-based, project-based, or activity-based learning incorporating ICT resources.

In contrast to these broad approaches to science BLEs, Longo (2016) proposed a guided-inquiry approach within a science specific BLE to support a variety of contexts for real world problem solving, individual and peer learning, and ongoing assessment, in both synchronous and asynchronous settings. Longo (2016) suggested that inquiry-based BLEs increased student motivation, creativity, critical thinking, and were reflective of the epistemic practices of scientific thinking. He also indicated a guided-inquiry approach suited adolescent learning by providing enough structure, support, and flexibility across the modes to accommodate students’ preferences and provide opportunities for differentiated learning.
The development of a science specific BLE frameworks need to address the interactions of key components specific to this subject. Bidarra and Rusman (2017) developed a conceptual framework to support learning science in a BLE: The Science Learning Activities Model (SLAM). SLAM is organised by possible practices afforded by context, technology and pedagogy, each presenting a continuum of practice (e.g., formal/informal, individual/collaborative, asynchronous/ synchronous, structured/open guidance). SLAM advocates for best teaching and learning practices in contemporary science education. It aims to holistically incorporate broader learning opportunities in and out of formal classrooms (e.g., practical investigations, field trips), open and creative pedagogies (e.g., inquiry), and appropriate technology to support dynamic meaning-making practices, to engage students in science and STEM. The SLAM model provides a flexible learner-centred design approach for a science BLE that can be adapted by both the teacher and learners according to their needs and context.

Within these flexible guided-inquiry approaches, science education researchers have investigated how interactive designs supported individual students’ learning pathways. One of the earlier and most widely adopted designs is the Web-based Inquiry Science Environment (WISE), a flexible authoring environment that incorporates digital scaffolds and tools to support inquiry approaches to learning secondary science. The platform allows teachers to embed prompts (e.g., hints) and resources (e.g., simulations, drawing tools) within a structured learning sequence. The WISE collection consists of a series of lessons constructed, refined, and tested by cross-country and interdisciplinary design teams, and can be customised by teachers (Linn, Clark & Slotta, 2003; Slotta &
Linn, 2009). The overall design follows four main guidelines: to make students’ thinking visible (e.g., reflection, modeling), to make science accessible (e.g., socio-scientific case studies), to support peer-to-peer learning (e.g., structured collaborations, peer review, debates), and to promote lifelong learning (e.g., autonomy, project-based learning). The lessons follow a customisable inquiry-map to track students’ patterns along with prompts to guide their explorations and encourage metacognition (e.g., monitoring, predicting) and knowledge integration (e.g., critiquing, interpreting, explaining).

Other adaptive web-based learning environments have incorporated open and interactive pedagogies (e.g., inquiry) in their design resulting in more personalised science learning experiences through algorithms customised to students’ learning progressions and preferences (She & Liao, 2010; Panjaburee & Srisawasdi, 2016). She and Liao (2010) developed a web-based adaptive learning system that supported ongoing adjustments to the individual’s learning based on their responses. Their design was based on conceptual change theory to support scientific reasoning, including probing students’ prior knowledge and scaffolding them through an inquiry processes (e.g., predictions, construction of explanations). She and Liao (2010) investigated middle school students’ conceptual change and scientific reasoning as they learned about atoms using an online digital learning environment. Activities began with conceptually-based questions where students’ responses would trigger a customised response providing them with information and resources (e.g., illustrations, animations, simulations, analogies), guiding them towards conceptual change. Results demonstrated improved conceptual understanding and reasoning processes.
Another example combined an online learning platform with tools to support learning chemistry. *Chemsense* was a researcher-designed multimodal science-specific software package that was used to scaffold a Year 11 chemistry unit. The platform integrated multimodal tools (e.g., digital probes, simulations, representations) with hands-on experiments and student-student collaboration (e.g., online discussions, peer reviews) within a classroom setting (Michalchik, Rosenquist, Kozma, Kreikemeier, & Schank, 2008). The investigation focused on conceptual understanding and the ability of students to generate and coordinate chemistry representations to support reasoning. The research design included pre- and post-questionnaires and videotaping, in addition to using rubrics to assess students’ meta-representational competence. Both qualitative and quantitative results indicated that students exhibited a deeper understanding of chemistry through developing their meta-representational competence and engaging in conversations in a similar manner to practicing chemists (e.g., discussing the affordances and constraints of representations, posing questions, reasoning, making claims). The researchers also emphasised the importance of teachers’ understanding of content, along with their ability to develop sequenced activities, link content to the curriculum, and scaffold discourse to support student learning.

Although the quality of learning associated with exclusive online learning is mixed (Means et al., 2009; Barbour, 2014), classroom settings where teachers blend face-to-face and online interactions show more promising outcomes (Michalchik et al., 2008; She & Liao, 2010; Slotta & Linn, 2009; Wendt & Rockinson-Szapkiw, 2014). These teacher-facilitated approaches are also thought to be a more appropriate choice for K-12 learners who require more guidance (Longo, 2016; Means et al., 2009).
My research setting involved teacher orchestration of face-to-face and online interactions using the Student Teacher Interactive Learning Environment (STILE) in a classroom setting. Though the students did not specifically use the out-of-classroom affordances of a BLE, the teaching and learning potential and the challenges presented were similar and the BLE research thus provided a reference point for the innovation in my research setting. STILE is an example of an interactive learning platform, with all the broad functionalities proposed by Richard and Dede (2012), in addition to being a customisable tool designed to support open-ended multimedia and multimodal approaches to science and STEM in K-12 education settings. Key features include digital concept mapping and drawing tools, assessment tools and real-time data analytics. Using the authoring capabilities of STILE, our research team incorporated the evidence-based active knowledge construction pedagogy of RCA to scaffold the learning sequences. The learning context was a physics unit about energy transfer, which incorporated additional multimodal technologies to support active knowledge building processes.

2.3.3 Digital technologies for learning science

Given the relationship between science and technology, science classrooms naturally integrate a variety of digital resources (e.g., multi-dimensional and dynamic representations, animations, simulations, virtual labs), and technologies such as data capture devices, calculators, and communications devices (diSessa, 2004; Gilbert, 2008). Although many of these digital resources are designed as instructional material prepared by experts (i.e., EGRs), some also support students to engage in active meaning-making processes as they create and share their own ideas in ways that were not previously available (Yore & Hand,
2010). The following examples highlight digital technologies that support these student-centred processes pertinent to my research setting. The first example involves *slowmation*, where students generate and coordinate multiple representations, through small group collaboration to create stop-motion animations to explain a scientific concept.

Brown, Murcia, and Hackling (2013) investigated how a mixed aged group of primary students engaged with *slowmation* to learn about astronomy. The researchers explored the quality of students’ discourse, the affordances of representational modes, and how the students demonstrated their understanding of concepts in astronomy. In addition, the researchers collected and analysed student artifacts for evidence of understanding. They indicated that the slowmation process was mediated through the creation, use, and refinement of multimodal representations (e.g., texts, diagrams, models, role-play) that culminated in a narrated multimodal video. The researchers concluded that students engaged in substantive science discourse around the content and task as they constructed multimodal representations of concepts, along with a high degree of collaboration. However, some students maintained common alternative conceptions about the topic, suggesting a need for a more in-depth conceptual focus. To effectively use slowmation to scaffold learning sequences, Brown et al. (2013) suggested teachers focus on developing students’ skill in collaboration and discussion, including the use of relevant digital software.

This example of slowmation involved learning sequences where students actively created, refined, and shared their ideas through a multimodal integration of non-digital and digital media as they engaged in ongoing scientific discourse and small group collaboration. The approach addressed the challenge of
conceptual change involving intuitive ideas around observable processes, linking students’ everyday experiences of the Earth, Moon, and Sun with models to address their ideas. The results suggest a promising role for dynamic digital technologies to support conceptual learning.

The next two examples involve software that enabled students to create dynamic digital models to learn scientific concepts at a molecular level. Digital technologies such as animations and simulations have special affordances in assisting students to visualise otherwise unobservable phenomena and processes (Tasker & Dalton, 2008), addressing a central challenge in teaching science involving the need to link the observable (i.e., macro) with the submicroscopic and symbolic levels (Johnston, 1991).

The following intervention study looked at the use of animations in Year 11 students learning chemistry. Hilton and Hilton (2013) reported on a case study comparing the learning of two classes that followed a researcher-designed and delivered six-week unit with a conceptual and multi-representational focus, including practical investigations. Both classes used specific molecular modeling software, animations and simulations, as the intervention. The researchers chose ChemSketch to support molecular modeling because it allowed students to create and manipulate models in a range of modes and integrate them into multimodal texts for sharing and evaluation. The software was free, adaptable to multiple year levels, and easy to use for both teachers and students. In addition, the researchers also integrated a simulation program, Molecular Workbench, which was selected because the activities could be edited to suit the teaching and curricular goals, and the students’ needs. The learning activities were self-paced, allowing students to monitor their own understanding.
Students were introduced to the software with which they completed a range of structured activities to create and interpret molecular representations. They were guided through the use of task sheets with questions requiring students to respond by creating, manipulating, and integrating molecular models. After the practical investigation, they also used these digital technologies to explain their observations. In this way, students were creating and using dynamic representations to solve problems. Both classes undertook the same pre- and post-tests, which consisted of a nine-item multiple choice test on chemical bonding, along with three open-ended responses. The results indicated students’ improved conceptual understanding and an ability to create, select, and use representations to communicate their understanding; post-unit interviews also indicated an increase in their motivation and engagement in learning.

The final example also involved an intervention study in a Year 7 inquiry-based science unit integrating animation software into a 10-week unit on matter. Chang, Quintana, and Krajcik (2010) chose Chemation, which enabled students to design, view, interpret, and evaluate simple molecular animations to understand the particle model of matter. The researchers created three treatment groups which differed in the extent of their use of the software to generate and use representations: one group used it to design, interpret, and evaluate animations; the second group only to design and interpret animations; and the third group used the software to view and interpret teacher-made animations. In each of these examples, students were guided in generating their own digital animations, resulting in improved conceptual understanding of challenging scientific processes. The results indicated that first approach was the most effective in improving student learning. Central to the success of these digital innovations
were the teacher-guidance of students’ and active engagement in knowledge construction.

In summary, these digital innovations combined with evidence-based approaches address some of the key issues related to the productive integration of digital technologies to improve learning outcomes in science. Given the technical nature of science and the increasing use of computers for representation-focused approaches, there is a need for research to build an understanding of how students are learning in these digital environments (diSessa, 2004; Lemke, 1998a; Yore & Hand, 2010).

2.4 Outline of my Research Focus

The digital approaches described in this section suggest promising results for the productive integration of ICT to support active knowledge construction processes, particularly with interactive online learning platforms. This potential aligns with my research focus: to investigate how a digital learning environment designed with an inquiry-based representation construction approach engages students in learning science. Given the widespread access and use of computers by Australian students in schools and at home, the accessibility of the STILE platform presents a viable solution to the meaningful integration of digital technologies used in conjunction with evidence-based pedagogies.

My research takes place in a digital learning environment that applies an active knowledge-building pedagogy scaffolded within an online learning platform, with the teacher orchestrating classroom-based multimodal face-to-face and online activities in a unit on energy transfer. My questions orient around the capacity of the DLE to support the active processes that more closely emulate scientific practices. My research questions are:
1. What were the generative features of this digital learning environment in supporting an inquiry-based representation construction approach?

2. How did the summative inquiry task support epistemic processes representative of scientific practice?

3. What were the patterns of conceptual and representational development in response to representation construction approach in this digital environment?

4. What are the implications for the design of digitally-based representation construction approach units?

The outcomes of my research will contribute to knowledge of how digital technologies support quality learning outcomes in science. The next chapter describes my research methodology for an ethnographic case study of a classroom that is integrating inquiry-based student-generated representation construction with digital technologies.
Chapter 3. Methodology

This chapter is organised into two main sections. Firstly I provide the rationale for my research approach and then describe my research design. The rationale focuses on how my research situates within the qualitative paradigm as an ethnographic case study. My research design elaborates on my research setting, theoretical framework, approach to data generation and analysis, data quality, and my role as a researcher.

3.1 Rationale for Research Approach

To gain insight into how students learn in this complex environment, I employed an ethnographic case study within the qualitative research paradigm to guide and support my research focus: to investigate how a digital learning environment designed with an inquiry-based representation construction approach engages students in learning science.

3.1.1 Qualitative research

My research situates primarily within a qualitative research paradigm, emphasising the co-constructed realities and meaning making of the researcher with the participants through multiple data generation methods. I also used quantitative methods to compare students’ pre- and post-test results. Multiple methods enabled me to construct a more comprehensive interpretation of students’ experience (Denzin & Lincoln, 2013). Within this interpretive approach, I was able to create/construct and create knowledge through an “iterative dialectic” that enabled me to make sense of and interpret students’ experiences using reasoned arguments informed by the literature (Schwandt, 1998, p. 243).

Through this approach to social inquiry, qualitative research attempts to explain how people make sense of their world. Qualitative researchers interpret
people’s lived experiences in context through multiple methods to understand how people make meaning for the purpose of improving a practice (Schwandt, 1998). The construction of knowledge is considered an accumulation of more informed and sophisticated reconstructions (Denzin & Lincoln, 2011). The quality of the findings is reflective of the information given to the researchers and their ability to interpret it (Denzin & Lincoln, 2011). Ultimately, the researcher provides a more informed understanding/construction/reconstruction of the lived experience while being open to further interpretation (Lincoln, Lynham, & Guba, 2013). In my study, the interactions among the students, teachers, and their social material environment provided insight into students’ experiences in this setting. The qualitative research paradigm supported my ethnographic methodology with enough flexibility to support a responsive research design in this dynamic learning environment (Denzin & Lincoln, 2013).

Following the principles of qualitative research, I applied specific language in my investigation: As the researcher/inquirer, I addressed myself in first person; data generation involved the active and co-constructive interpretive process with participants/informers; the outcome of data generation and analysis were interpreted as findings; findings were not verified, but quality criteria were applied to ensure trustworthiness and authenticity (Lincoln, Lynham, & Guba, 2013); triangulation of data was not used for validation, but added rigor, breadth, and depth to the investigation; quality criteria also included credibility, transferability, dependability, confirmability (as opposed to internal and external validity, reliability and objectivity) (Denzin & Lincoln, 2013).
3.1.2 Ethnography

My investigation followed an ethnographic methodology with a case study approach. As a qualitative approach to social inquiry, ethnography is associated with the researcher embedded in the context and culture to develop relationships with the informants, resulting in a more in-depth understanding of the phenomena under study (Teddlie & Tashakkori, 2009). As a methodology, ethnography is “an approach to experiencing, interpreting, and representing” a research setting or phenomena such as the learning that takes place in a classroom (Pink, 2007, p. 21). For my classroom-based ethnography, I attended most of the lessons and situated myself as a participant-observer, observing the rules and behaviours of the school and classroom to minimise disruption (Jupp, 2006). I recorded field notes during classroom observations to provide contextual data for my analysis (Derry et al., 2010).

Ethnography is increasingly used in studies investigating human-technology interactions and is effective for capturing the tacit and explicit knowledge development and learning through conversation, gestures, interactions and actions, (Cohen, Manion, & Morrison, 2013), so it was well suited to my research design. The use of multiple methods (e.g., participant observation, interviews, artefacts) was commensurate with this approach and enabled me to develop an in-depth understanding of the multiple perspectives, experiences, and interpretations in context (Jupp, 2006; Pink, 2007).

3.1.3 Case study

Within the ethnographic methodology, I used a case study approach. Ethnography and case study are complementary and share similarities, with case study providing a more in-depth investigation of a specific case or phenomenon
(Cohen et al., 2013; Denzin & Lincoln, 2011; Yin, 2014) and a practical method for complexity reduction (Klette, 2009). The case study approach enabled me to narrow the focus and timeframe within the broader ethnographic view, so I could better re-construct a real-world account of the dynamic interactions and relationships (Cohen et al., 2013; Yin, 2014). This approach was also suited to understanding sense-making practices in context (Flyvbjerg, 2006).

While the overarching case is the class undertaking the unit of work, I chose a single group as a unit of analysis to focus on the fine-grained details of students’ interactions with the materials and learning pathways. Information about the choice of school and class are addressed in Section 3.2.1. The potential case groups were initially decided through convenience sampling, following the teacher-directed recommendation about groups who would be most amenable to be videoed (see Section 3.2.3). Following Furberg, Kluge, and Ludvigsen, (2013), one group presented the most comprehensive data set along with the strongest capacity to verbalise their reasoning with one another. This group also indicated one of the biggest learning gains, with initial pre-test results below the class-average (see Chapter 7). From students’ generated outputs, it was possible to get a sense of both their individual and co-constructed understanding of the concepts, showing how understanding shifted among individuals and tools, and how they came to a consensus. This crystallisation of meaning making within the group over time provided insight into the multiple perceptions and different perspectives within this case (Stake, 2005). Because of the unique nature of case studies, my findings were not meant to be generalisable (Cohen et al., 2013; Jupp, 2006). In my study, the findings extended an understanding of representation-focused approaches in a digital learning environment. This was consistent with role of
case studies in adding insight into existing theories and to develop new ways of thinking that may lead to educational change (Denzin & Lincoln, 2011; Cohen et al., 2013; Yin, 2014).

3.2 Research Design

In this section, I outline my research design along with the methods used to generate, analyse, and communicate the data. Research for this investigation took place in a secondary school where students were learning about energy transfer (i.e. physics) in a digital learning environment. My research design was informed by a DCog theoretical framework. Data generation included participant observation with video capture, semi-structured interviews, artefacts, pre- and post-tests, a questionnaire, and the researcher’s journal. The following section provides information about the research setting, including the school, curriculum, the learning environment, and participants.

3.2.1 Research setting

Research for this investigation took place at St. Helena’s College, an all-girls independent Catholic Secondary school in Melbourne, Australia, over a three-month period. The College offers courses and programs from Years 7-12, including the Middle Years Programme (MYP) in the International Baccalaureate Organisation for Years 7-10. St. Helena’s College offers courses required for the Victorian Certification of Education (VCE) as well as programs for the Vocational Educational and Training qualifications. In Years 11-12, students are required to take at least one science course to qualify for graduation and can select from Biology, Chemistry, Physics, and Psychology. Thus, students could attain a secondary school completion certificate at this school that would support ongoing education at a tertiary level, such as universities and vocational institutes.
In 2015, St. Helena’s College was ranked in the Top 10 Catholic Girls’ Schools according to students’ results in the mandatory VCE coursework. Approximately 900 students attend this school.

The choice of working with this particular school, teacher, and class was based on convenience sampling. St. Helena’s College was one of a group of iSTELR schools in Melbourne participating in the ARC digital inquiry project outlined in Chapter 1. This was their third year of participation. During an ongoing professional development session, the science teachers were presented with the idea of having a researcher in their class. All of the teachers were amenable to the idea. In March 2016, at the beginning of the Term 2, I visited each of the six Year 9 science classes and spoke with all teachers. Our conversations highlighted their experiences in teaching science, their experiences with iSTELR, their understanding of and facility with RCA, and how their students would receive a researcher in their classroom. After these conversations, I identified two possible teachers who best fit all of the above criteria, and chose the one with a stronger background in RCA and greater facility with the STILE platform to support the best quality of data.

Curriculum

St. Helena’s College follows the Australian National Curriculum. The learning area, general science, is a required course in Years 7-10 with sub-disciplines of biology, chemistry, and physics. This investigation focused on a Year 9 science class studying the physics component on energy transfer (Australian Curriculum, Assessment and Reporting Authority [ACARA], 2018, ACSSU182). The content description is written thus, “Energy transfer through
different media can be explained using wave and particle models”, with the following elaborations:

…exploring how and why the movement of energy varies according to the medium through which it is transferred; discussing the wave and particle models and how they are useful for understanding aspects of phenomena; investigating the transfer of heat in terms of convection, conduction and radiation, and identifying situations in which each occurs; understanding the processes underlying convection and conduction in terms of the particle model; exploring the properties of waves, and situations where energy is transferred in the form of waves, such as sound and light (Physical sciences section, para. 4).

Whereas the content description are prescribed and required, the elaborations are suggestions from which to guide the design of the classroom-based curriculum. For the unit in this investigation, all elaborations listed above were addressed. The next section outlines how the prescribed curriculum was integrated into the unit.

Design of the energy and sustainable housing unit

The Year 9 Energy Unit was designed to be incorporated into the STILE platform, integrating RCA throughout each lesson. To develop and refine this unit, one of the chief investigators of the ARC digital inquiry project collaborated with the team of Year 9 science teachers, including the case teacher, and ran professional learning workshops. They began by connecting the content strand with the other two strands in science: Science as a Human Endeavor and Science Inquiry Skills. The team identified climate change and sustainable housing as the contemporary socio-scientific issue from which to base the unit on. From the
content and elaborations, they identified key scientific concepts along with their alternative misconceptions and proceeded to develop modules based on the teaching and learning of concepts in this context.

To incorporate RCA, the team considered the affordances of the face-to-face and online learning environments in supporting this inquiry-based approach across digital and non-digital media. Interactions included: semi-structured open-ended inquiry-based exploration; individual, small-group and whole-class discussions; activities (e.g., viewing videos, constructing representations, conducting practical investigations); and assessments (e.g., multiple choice questions, summative inquiry task). By engaging in these intentionally sequenced activities, students learned about the fundamental concepts in energy (e.g., particle theory, heat transfer, conduction, convection, radiation) and how these concepts inform the design of a sustainable home, ultimately applying their knowledge to the summative inquiry-based task. The unit as planned was sequenced over 12 modules on the STILE online learning platform by one of the chief investigators on the ARC project, including the pre- and post-test. Table 3.1 outlines the modules in STILE.
### Table 3.1

**STILE Modules, Key Ideas, and Synopsis – as Planned**

<table>
<thead>
<tr>
<th>Module</th>
<th>Key Ideas</th>
<th>Synopsis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Introduction</td>
<td>• Energy transfer through different media can be explained using wave and particle models.</td>
<td>Students complete an online survey of their prior knowledge (i.e., pre-test) and construct an energy <em>Word Cloud.</em></td>
</tr>
<tr>
<td></td>
<td>• A knowledge of energy transfer involving energies associated with light and thermal energy inform the best practices associated with the use and transfer of energy in sustainable houses.</td>
<td></td>
</tr>
<tr>
<td>2. Attitudes to Climate Change</td>
<td>• Australians have varying ideas about the existence of causal reasons for climate change.</td>
<td>Students participate in a <em>Live Poll</em> to compare their attitudes on climate change with those of other Australians, based on a survey created by the Commonwealth Scientific and Industrial Research Organisation (CSIRO).</td>
</tr>
<tr>
<td></td>
<td>• Australians vary in their trust level about who gives them information about climate change.</td>
<td></td>
</tr>
<tr>
<td>3. Climate Change: The Evidence</td>
<td>• Climate change is happening.</td>
<td>Students engage with the online activities, videos, and representational tasks, including constructing a mind map on greenhouse gases.</td>
</tr>
<tr>
<td></td>
<td>• The environment is changing: average global temperatures are rising; carbon dioxide levels are increasing in the atmosphere; extreme weather events are more prevalent; polar icecaps are diminishing.</td>
<td></td>
</tr>
<tr>
<td>4. Introduction to Sustainable Housing</td>
<td>• A sustainable house uses passive elements to minimise the amount of energy needed to heat and cool the house.</td>
<td>Students engage with the online activities, video, and representational tasks, including constructing a concept map on passive design strategies.</td>
</tr>
<tr>
<td></td>
<td>• The rest of this topic will explore the ways in which we can minimise our household energy use through the construction of houses that have passive design elements.</td>
<td></td>
</tr>
<tr>
<td>5. Temperature and Thermal Energy</td>
<td>• The temperature of an object is related to the average kinetic energy of the particles that make up the object.</td>
<td>Students complete an online quiz to survey their prior knowledge. They engage with a series of representational challenges, as well as a role-play.</td>
</tr>
<tr>
<td></td>
<td>• The thermal energy of an object relates to the total kinetic energy (movement) and of the particles that make up the object.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Heat is the energy that gets transferred from hot objects to cooler objects.</td>
<td></td>
</tr>
</tbody>
</table>
| 6. Heat Transfer: Conduction | • Energy can be transferred from one system to another (or from a system to its environment) in different ways: by conduction, convection, or radiation (electromagnetic waves).  
• Conduction is the transfer of energy between objects that are in physical contact.  
• Convection is the transfer of energy between an object and its environment, due to fluid motion either in a gas or liquid.  
• Radiation is the transfer of energy from the movement of charged particles within atoms that is converted to electromagnetic radiation which can travel through space.  
• Energy can be transformed from one form to another. Changes occur when energy is transformed and these changes may be observed and measured.  
• Energy cannot be created or destroyed, but only changed from one form into another. When energy changes in form the total amount of energy remains constant.  
• In systems undergoing change, energy spreads out from the source. This is called dissipation of energy. | Students engage with the online activities, videos, and representational tasks. They conduct a heating investigation using dataloggers. |
|---|---|---|
| 7. Heat Transfer: Convection | • Energy can be transferred from one system to another (or from a system to its environment) in different ways: by conduction, convection, or radiation (electromagnetic waves).  
• Convection is the transfer of energy between an object and its environment, due to fluid motion either in a gas or liquid. | Students engage with the online activities, videos, and representational tasks. They investigate convection by constructing a teabag rocket. |
| 8. Electromagnetic Radiation: What is it? | • Light is a general term for electromagnetic radiation which is emitted from objects that contain moving charged particles (e.g., electrons).  
• Light is electromagnetic radiation which is a form of energy caused by electric charges (often, electrons) that are vibrating.  
• Light is an entity that travels through space at the speed of light (300,000 km/s) in straight lines until it interacts with something.  
• The electromagnetic spectrum is the range of all types of electromagnetic radiation. In increasing energy these types are Radio waves, Microwaves, Infra-Red, Visible, Ultraviolet, X-Ray and Gamma Radiation. | Students engage with the online activities including simulations, videos, representational tasks, and challenges. |
| 9. Visible Light and Vision | • In this module students will get an understanding of the processes that occur in the eye for a person to be able to see. In explaining how the eye ‘sees’ something we draw ray diagrams where: rays are represented by arrows that show the direction of light energy. | Students participate in a live poll to compare their prior knowledge about light and engaging in representational tasks. |
10. Heat Transfer in a House
- Heat transfer can occur by conduction, convection, or radiation.

Students engage with the online activities, and representational tasks, including conducting a thermos investigation.

11. Sustainable House Task
- A passive system is one that uses only locally available energy sources and utilises natural energy flow paths in and around the house. In other words, no auxiliary equipment (such as fans or pumps) are required to make the system function.
- Passive design is a design principle that takes advantage of the climate to maintain a comfortable temperature range in the home. This can save energy, water and money, while creating a more enjoyable and comfortable environment for its occupants.

Students engaged in an inquiry to investigate passive design strategies used in designing sustainable houses.

12. What I now know about Energy

Students complete the same questions presented in the pre-test to compare their learning over the unit.
The teacher planned the unit over 12 lessons (e.g., classes, periods) during Term 2, from March 18th, 2016 to May 10th, 2016. Science class was scheduled on a 10-day timetable, occurring two or three times a week, with classes 60–75 minutes in duration. I attended most of these classes. The unit as experienced is addressed in Chapter 4.

The learning environment

Instruction took place in the physical space of the science classroom. The room had desks and chairs arranged in six groups seating four to six students, along with an area dedicated to formal scientific laboratory investigations (e.g., fixed laboratory benches, sinks, gas supply). Both areas were used based on the activities in a given lesson.

The online learning platform, STILE, was accessible via the internet and featured all the modules for the unit. At the beginning of the school year, students received a laptop for their own personal use in all subject areas. For the 2016 school year, Year 9 students received an HP Elite x2 1012 laptop. The laptop features included a removable keyboard, Active-Pen™ technology, and a built-in camera. Students were required to bring their laptop with them to all classes, including science. With it, they could access all school approved internet-based resources, the online learning platform, as well as relevant programs and applications (e.g., Microsoft Word processing programs, timer, camera).

Student Teacher Interactive Learning Environment

STILE is an online learning platform that supports a variety of activities in a cloud-based learning environment, facilitating both face-to-face and online interactions. The platform can be accessed in the classroom, from home, or anywhere with an internet connection. The interactive online platform provided a
variety of digital features including: multimedia (e.g., digital images and photographs, audio, videos, simulations, PDF documents, links to the internet), a live poll facility that visually aggregates whole-class responses, interactive fill-in-the-blank tables, a *Written Response* application with an *infinitely expanded ruled pad* in which to record answers, and assessments (e.g., multiple choice, true and false). STILE allowed students to upload their digital artifacts (e.g., documents, PDFs, images, video) for ongoing formative assessment. STILE also has an *Interactive Canvas* that allowed students to draw diagrams, construct mind maps, and integrate multiple media. Once students recorded or uploaded their work in STILE, the teacher was able to access it online anytime (i.e., during class or outside class instructional time) and assess it either through the platform or as a whole-class activity. The *Markbook* feature supported individual and class level analytics of students’ completed work and also indicated if students accessed, viewed, and completed the activities. In addition to the online learning platform, students were also able to write or draw in their individual project books, which were distributed at the beginning of the unit. These books contained both lined and unlined pages to accommodate text and drawings.

*The participants/informants*

The teacher, Sophie (a pseudonym) was a mid-career science teacher with a science degree in nutrition and genetics and a teaching degree. She had taught biology and junior science in Melbourne schools for the past 10 years and has a professional interest in using representations in the science classroom and in integrating technology. This was her third year using the STILE online learning platform and integrating RCA. There were 27 students, most of them 14 years old and in their second term of a total of four terms in the school year. This was their
first time using the STILE platform. Students in the case group are formally introduced in Chapter 5. To understand the learning in this unique setting, I employed multiple methods within this ethnography, guided by my theoretical framework.

### 3.2.2 Theoretical framework: Distributed cognition

DCog is a key theoretical framework that underpins my research design and analysis. In this section, I explain how DCog applies to researching learning environments, and justify its inclusion as part of my research design. DCog describes how cognition is distributed across people, resources or tools, space and time, in relation to a specific task (Hutchins, 1995, 2014; Zhang & Patel, 2006). In contrast to a psychological view, which approaches learning as an individual process, DCog considers learning as a social and material phenomenon, (Hutchins, 1995; Moore & Rocklin, 1998). As a contemporary socio-cultural theory of cognitive science, learning is inextricably linked to context, encompassing social interactions, mediating tools, and cultural practices (Tenenberg & Knobelsdorf, 2014). Within this cognitive system, no single element holds all the information and the centre of learning can shift or be distributed equally among all elements (Hutchins, 2014). Elements guide and constrain people’s interactions, resulting in emergent behaviours that are distinct and more substantial than their constituent parts (Hutchins, 1995; Pea, 1993; Zhang & Patel, 2006).

DCog situates within a task. The theory maintains that knowledge (i.e., an outcome of the learning process) is socially constructed and actively developed through completing tasks in context, rather than static content to be absorbed by individuals (Pea, 1993; Salomon, 1998). The task thus needs to be complex
enough to require collaboration and problem solving (Salomon, 1998). Learning is observable through the ideas and strategies used to negotiate the learning tasks (Hutchins, 1995; Taber, 2013). DCog provides a framework and analytic methodology to identify and understand the complex interdependencies between and among people and the tools they use in their collaborative activities (Rogers, 1997; Zhang & Norman, 1994). Understanding the affordances and weaknesses in context enables insight into effective design (Angeli, 2008). It does this by providing more information on the interactive nature of the tools and processes that support a task than can be gained from just reviewing the output of the task (Halverson & Clifford, 2006). The mediating role of social and material interactions for learning has implications for education research, including my own.

Mediators for learning in this digital learning environment

In my research setting, RCA involves the socio-cultural process of collaborative knowledge construction through multimodal resources. The DLE provided both digital and non-digital tools and other semiotic or representational resources from which to construct and share knowledge. To understand the mediating role of the social and material interactions as a distributed system, I focused my analysis of the learning process on the following three elements: the social interactions among students and with the teacher, and students’ use of digital and non-digital technologies (i.e., representational resources). I elaborate on each of these elements, including the context and the task.

Social interactions

The role of social learning is well established in education (Vygotsky, 1978) and has an important role in DCog theory. In DCog, communication occurs
through mediating artifacts such as language or representations (Hutchins, 1995). This theory is most effective when the learning task is complex and requires dialogue and collaboration among a group of learners. The emergent properties of group collaboration are influenced by efficacy, flexibility, and differentiation. The efficacy of a group depends on the size of the group, their ability to share their respective cognitive resources, and the task (Hutchins, 1995; Zhang & Patel, 2006). A distributed system provides flexibility due to the overlapping skills or knowledge among individuals (Hutchins, 1995) and affords differentiation in an education setting. In a given group, there may be differences in students’ prior knowledge and experience related to the content, collaborative and problem-solving abilities, and their ability to use tools such as digital technologies. DCog assumes that collectively, a group possess the knowledge and skills to complete the task. In this way, the task supports individual differences and enables all group members to participate according to their ability.

Hutchins (1995) argued that collective cognition for a task is generally more efficient than that of an individual. However, if a group is ineffective in communication, sharing skills and knowledge, or coordinating tasks, the outcome can also be worse than that of an individual (Zhang & Patel, 2006). For example, the risk for dominant behaviours could limit the sharing of diverse ideas and solutions in problem solving, or influence decisions, even if most individuals are not in agreement. Hutchins (1995) argued that the difference in output between groups is attributed more to how people were organised to perform a task, than on the cognitive potential of single individuals. To support effective DCog for group tasks thus requires the selection or monitoring of members within a group, clear expectations and support for group skills, and design of group tasks (Pea, 1993).
The teacher has an important role in creating and supporting an effective collaborative learning environment.

The science class in this investigation had a cultural history of group-based collaboration, supported by a learning space with grouped desks, and a separate area for laboratory benches. The desks were arranged into six groups and students assembled themselves into groups of their choice, with fairly consistent membership throughout the unit. The three students I identified in the case group consistently worked together throughout the unit, including during the summative task. DCog analysis of the social interactions provided insight into the nature of the dialogue, interactions with the representational resources, and the extent of collaboration within this distributed system.

**Material interactions**

Socio-cultural perspectives view learning as a result of participation in the tool-mediated practices that cultural groups use for addressing tasks within authentic settings (Tenenberg & Knobelsdorf, 2014). DCog identifies the role of the mediating tools in supporting the epistemic practices of a given discipline (Hollan et al., 2000). In this setting, RCA emulated the epistemic practice of knowledge construction, and the DLE provided a broad range of digital and non-digital multimodal representational resources for this purpose. Learning to construct knowledge through these resources is as important as the knowledge itself: they are interrelated processes (Hutchins, 1995; Lemke, 1998b, 1998c). Learning requires students to use the tools and is also an outcome of tool use. This coupling offers insight into the design of tools, learning systems, and the task itself (Pea, 1993; Salomon, 1998; Tenenberg & Knobelsdorf, 2014; Zhang & Norman, 1994). One example is how students’ use of the cloud-based platform
provides insights into its ability to support knowledge construction with the potential to expand the dimensions of space and time through digital and online resources.

DCog is particularly suited to provide insight into how digital technologies influence learning. Hollan, Hutchins, and Kirsh (2000) considered that computers access different temporal and spatial dimensions compared to analogic tools. Apart from just being content repositories, computers re-distribute intelligence, facilitate complex tasks, enable networked communication, and refine participation (Pea, 1993; Hollan et al., 2000). Historically, human-computer interface research focused on how individuals interact with digital technology, whereas DCog includes the broader context and provides insight into the reciprocal influence and engagement of humans with technology. In my research, this has implications in the design of the digital learning sequences within the cloud-based platform along with the summative inquiry task.

Describing tasks

The task is the purpose and driver of the learning in a DCog system. The quality of the task, and the social and materials tools and interactions to support the task are interdependent. The task must be complex enough to require the knowledge, experience, and skills of more than one individual to solve, and be situated within a real-world scenario to elicit an understanding of the cognition in context (Halverson & Clifford, 2006; Hutchins, 1995). In a science classroom, examples of such tasks include group projects and practical investigations. The unit of analysis includes the interactions within and across the elements during an activity or task (Hutchins, 1995; Halverson & Clifford, 2006; Zhang & Patel, 2006). Identifying and independently examining these elements within tasks
provides more insight into an effective cognitive system in context than just focusing on the output of a task (Halverson & Clifford, 2006; Zhang & Norman, 1994). For example, a students’ final laboratory report does not provide adequate information about the tools, processes, and nature of the interactions to support a complex practical investigation (Halverson & Clifford, 2006).

In my study, the energy unit was designed in collaboration with science teachers to focus on concepts of energy transfer through a relevant context of sustainable housing. Each module included a variety of activities for students and groups, culminating in a complex summative task. Throughout, students engaged in the activities and generated a variety of learning outputs (e.g., diagrams, role-plays, final reports) through multiple interactions and pathways, adding insight into their learning processes (Hutchins, 1995).

**DCog as it applies to my research design**

As a theoretical framework, DCog situates cognition beyond an individual to include the social and material environments and is consistent with the cognitive, socio-cultural, and socio-semiotic perspectives that inform learning through the RCA. DCog is suited to my research setting, which consists of a complex digital multimodal learning environment, where learning is mediated through social and material interactions.

The DCog framework was consistent with my ethnographic approach, including the use of audio and video recording to capture the active nature of distributed systems, particularly those involving human-digital technology interactions (Hollan et al., 2000; Rogers, 1997). In this DLE, the elements include small and large group interactions (e.g., dialogue, activities), digital technologies (e.g., laptop, datalogger, STILE), and non-digital technologies (e.g., project
books, scientific apparatus). Students’ interaction with these elements enabled them to construct and apply their knowledge to perform tasks. Thus, DCog featured in my analysis of students’ learning pathways and included their interactions with the resources, connecting the products and processes of learnings as a distributed system. DCog was also a key organising framework in the summative task, which was a complex collaborative task involving multimodal representational resources. Figure 3.1 depicts the elements in this distributed cognitive system as they align with the methods for data generation, to support a comprehensive understanding of the interactions in this setting.
In summary, DCog focuses on interactions of students with their material and social environment, and the role of tools (e.g., representations, digital technology) in mediating their learning (Clarke, Xu, Arnold, Seah, Hart, Tytler, & Prain, 2011; Hutchins, 2014). I have chosen it as my theoretical framework to organise data generation and analysis for the following reasons: it is consistent with the multi-theoretical perspectives that inform representation construction; it regards learning as adaptive; it situates cognition within the broader environment; it considers the mediating role of tools on activities; it is particularly suited to the dynamic and multi-dimensional nature of digital technology; and it is
commensurate with my methodology. The following section elaborates on the methods I used for generating data.

3.2.3 Data generation

The methods supporting this ethnographic investigation included participant observation, field notes, video capture, interviews, artefacts, pre- and post-tests, and a questionnaire. Figure 3.1 organises these methods with the elements in the context of the distributed cognitive system. To begin, I elaborate on each of the methods used for data generation.

Participant observation

My professional experience as a classroom teacher, teacher trainer, and curriculum developer contributed to my position as an informed ethnographer. As a researcher doing an ethnographic study, I was embedded in the research setting (Pink, 2007) and established an intentional membership with community under research (Angrosino, 2005). I had already met the science teaching team the previous term and had established a rapport with them throughout their professional development sessions during the previous year and the year I conducted my investigation (see Section 3.2.1). My expertise as an educator enabled me to understand the complex interactions of the disciplinary-specific practices (Hollan et al., 2000; Rogers, 1997). I also found myself occasionally helping with clarifying procedures for students, and in my informal interviews with them, raising questions that helped with their reflection. Thus, I situated myself as a participant observer.

My participant observation existed on a continuum, from observation to full participation (Angrosino, 2005). As a researcher and a former science teacher, I found myself balancing the immediate needs of a dynamic and demanding
learning environment with the needs of a researcher (e.g., drafting field notes, maintenance of video equipment, conducting interviews). Depending on the lesson, my activities ranged from taking notes and monitoring the video cameras, to assisting with questions and technology-related issues, to co-instructing with the teacher (e.g., explaining the dataloggers). When the teacher anticipated being away for one lesson (i.e., Conduction Part 1 on April 12, 2016) I was invited to lead the class to maintain the representational pedagogy and lesson schedule.

Through field notes, I recorded my observations and experiences taken in the moment and/or retrospectively for each lesson, in coordination with my journal (see Data Quality). My observations were constructed through my interactions with the participants and other offsite researchers (Angrosino, 2005). Interactions included: ongoing dialogue; guiding students on how to use the video camera; interacting with students through the multiple modes of data generation; and co-presenting the research with the chief investigators and the classroom teacher. All of these interactions informed the ongoing construction of the unit as experienced. In addition to being physically present in the classroom, I also used video capture, an audio-visual technology, which is increasingly used in ethnographic research (Pink, 2007).

*Video capture*

The use of video in this ethnographic research provided additional information on phenomena, compared to the traditionally static nature of data collection (Pink, 2007). Rather than merely a medium from which to translate to verbal or written texts, video capture offered a distinctive mode of data generation, with its own interpretative affordances that complemented the other methods (Pink, 2007). Video capture allowed access to and preservation of
dynamic and naturally occurring interactions in context (Jewitt, 2012; Pink, 2007). It provided a comprehensive view of the phenomena, and with two cameras, captured the multiple perspectives inherent in learning environments (Clarke, Mitchell, & Bowman, 2009). The use of video chronicled the concurrent and multimodal nature of communication and interactions (e.g., discourse, gestures, representations, actions) (Cirkony & Hubber, 2018; Clarke et al., 2009; LeBaron, 2005).

The use of video enabled me to more actively engage as a participant observer in the research setting, freeing up time to take additional notes in situ and conduct interviews. Video also supported video-stimulated recall interviews (VSRI): when shared with the participants through video playback, they were able to speak directly to their experiences, enabling me to construct their lived reality and reduce researcher subjectivity (Clarke et al., 2009; Pink, 2007). Video was also used to inform ongoing data collection. As the study was underway, I reviewed video footage with my supervisory team to synthesise understanding and inform direction for future video capture of lessons (Pink, 2007). Through these affordances, video capture allowed for coarse and fine-grained multimodal analysis of learning in chronological sequence (Cirkony & Hubber, 2018; Clarke et al., 2009, Jewitt, 2012).

From a DCog perspective, video recording was suited to capture the events, activities, and interactions in context, as a distributed cognitive system (Hollan et al., 2000; Hutchins, 1995, 2014). The video record showed how the teacher and students interacted with multiple elements to perform tasks (Clarke et al., 2009; Clarke et al., 2011). Specifically, video captured the dynamic and multimodal context of how students chose and coordinated modes and tools in
relation to their dialogue and the task (Jewitt, 2012). Thus, the video record
provided evidence of cognition as “situated, social, embodied, and richly
multimodal” (Hutchins, 2014, p. 712). In summary, video ethnography captured
the multimodal nature of a science classroom, integrating digital technologies and
complementing other modes of data collection (e.g., field notes, artifacts)
supporting a more holistic understanding of the complex learning environment of
a classroom.

Recording video footage in the classroom

For my research, I used video-capture for seven of the eleven lessons
(though one lesson included footage of only a single activity). I used two free-
standing GoPro cameras with wide-angle lenses and attached microphones to
capture the student-group interactions (Figure 3.2). These small cameras were
unobtrusive, mobile, and familiar to the students, supporting more naturalistic
interactions, along with the ability to adapt to changing settings and activities
(Klette, 2009). The cameras were placed with two different student groups for
each class and remained with the group for the duration of the lesson. The camera
captured students’ faces, conversations, gestures, the materials in front of them
(e.g., laptops, project books, science apparatus), and their interactions as they
participated in activities.
Initial camera placement was based on convenience sampling in consultation with the teacher to ensure a positive uptake. For subsequent lessons, I decided where to place the cameras *in situ* based on students’ choice to be videoed. They were videoed in the groups they customarily worked in, providing a more naturalistic perspective of their interactions. Students were also encouraged to direct the camera to capture their work on their laptop or in their project book. The video capture took place for the duration of a given activity. By the last three classes, I focused on three groups, switching the camera among them to gather a more comprehensive data set.

*Viewing and processing the footage*

Immediately after each lesson, I viewed the footage in its entirety using Studiocode analytical software. Studiocode was initially developed to video-analyse sports-based activities and has been modified to include the methodological, theoretical, and practical needs of education research (Clarke, 2013). The software helped to organise and analyse the active nature of classroom
conversations and activities (Clarke, 2013). During the initial viewing, I drafted a timeline for the lesson, identified key instances of students’ interactions with representations, and recorded initial impressions, reflections, and possible codes (LeBaron, 2005; Jewitt, 2012). I followed an inductive and abductive (e.g., intuitive) approach with broad guidance from the research focus. These initial impressions enabled me to adjust data collection for following lessons and identify which activities needed to be revisited to ensure quality criteria were met (Denzin & Lincoln, 2013). From this footage, I also identified instances for follow-up interviews with the same students as video-prompts to assist their reflections (i.e., VSRI).

For data management, on the day the video data was collected, I transferred all the data from the memory cards into two separate hard drives. I also converted the files into a format that could be organised and analysed in Studiocode. Each week, data was backed up on a larger server and the memory cards were erased for re-use. The amount of storage required for the video data necessitated the use of multiple 2-terabyte external hard drives, which were encrypted to secure the data, along with a 1-terabyte Dropbox account for cloud storage. I created a data log to manage the different modes of data (e.g., video, artefacts, photographs, audio recordings). The multiple cameras and data generation methods provided a broad overview of the learning environment, assisting with developing a unit-wide ethnographic perspective. The cameras also facilitated a more fine-grained view of the multiple perspectives, assisting with a micro-ethnographic analysis, which is addressed in the Analysis section.
Interviews

Interviews enabled me to gain an understanding of students’ thinking, reasoning and attitudes, from their perspective. To prepare for the VSRI, I reviewed the video footage after each classroom visit and identified instances where students were reasoning with representations, making choices about modes and media, making key decisions about the task, and coming to consensus about key concepts. I also identified other tools students were using (e.g., project books, Google Docs), along with examples of their work (e.g., diagrams) that I used as prompts for their reflections during our interviews.

To ensure I kept within the scope of the research focus, I developed possible questions and prompts, associated with phrases, artefacts, and video-segments, for the face-to-face, semi-structured interviews to encourage more in-depth responses (Teddlie & Tashakkori, 2009). Most of the interviews were conducted with students in the groups in which they were filmed, or a smaller subset thereof, to minimize the possibility of power differentials and to assist with students’ comfort level in their interactions with me (Denzin & Lincoln, 2011; Cohen et al., 2013). The small group interviews also had the additional benefit of capturing the natural collaborative interactions between the students who were working together in this unit. Most of the interviews integrated video-stimulated recall, except for the post-test interviews. Students’ reviewed the video of their activities from a previous lesson, reflecting on their thinking at that time and elaborating on their decisions and conceptual understanding. Interviews were audio recorded using the audio application on my personal iPhone 5s, except for one which took place while the videoed group was working on their inquiry task. All interviews took place during school hours.
Artefacts

Artefacts included a broad selection of students’ responses, including representations from their project books, in the STILE platform, and their final reports. These artefacts constituted the multimedia and multimodal collection of students’ digital and non-digital representations over the duration of the unit, providing insight into the tools they used and the nature of their representations (Cirkony & Hubber, 2018; Hutchins, 1995; Hollins et al., 2000). Some artefacts were used as prompts during the VSRI. At the end of the unit, I digitally photographed students’ project books, downloaded or screen-captured their online work, and collected a digital copy of their final reports. Artefacts were then indexed by date and student, assembled into their respective modules, and organised by the case groups and their constituent students.

Pre- and post-tests (i.e., surveys)

Students began the unit with an online survey of their prior knowledge regarding key scientific concepts and commons misconceptions (Tytler et al., 2013b), then repeated the survey at the end of the unit for comparative purposes (Teddlie & Tashakkori, 2009). From a pedagogical perspective, the pre-test functioned as a formative assessment task by indicating students’ prior knowledge and enabling the teacher to adjust her teaching. From a research perspective, the tests were an additional method to assess students’ learning. The 15 question pre- and post-test comprised 12 multiple choice questions and three questions requiring the construction of representations. See Chapter 7 for my analysis of students’ responses.
The online questionnaire was developed to survey students’ experience in the DLE. The original intent was to facilitate a whole-class focus group session, but due to time constraints, I developed the questionnaire as an alternative. The questionnaire allowed students to share their perspectives on the unit as experienced, without my being present (Cohen et al., 2013). The primary purpose of this instrument was to relate students’ individual perspectives to my research focus. Questions oriented around my research intentions and enabled students to elaborate on their personal experiences in four major areas: key ideas/concepts, use of digital and non-digital technologies, experience during the Sustainable Housing Inquiry task, and their general experience of learning science in this unit.

I designed the 15-item online questionnaire using the STILE online learning platform, and featured it as a separate module (see Appendix A). This decision was based on the fact that the format was familiar to the students and enabled flexible access (e.g., in science class, during school time, at home). My design used a simple format with short answers and matrix-type layout for a more effective organisation of questions and economic use of space (Cohen et al., 2013). Fourteen questions were text-based questions, where students type their responses into the infinitely expanding ruled pad and one question was rank-ordered (i.e., ordinal). I designed the questionnaire to be completed in 15-minutes. Due to the small sample size (i.e., 27 students), I designed the instrument to be open-ended to allow for more elaborate responses (Cohen et al., 2013). The small sample size and open-question design also allowed for a more responsive development time with no need for the piloting of questions (Cohen et al., 2013). The questions were planned primarily for thematic analysis, with one Likert-scale
response item designed for a simple frequency analysis. Responses were addressed as part of students’ overall experiences with this unit.

Data generated

The full data set consisted of field observation notes (see Reflexivity in the Data Quality Section), video data, interviews, student artefacts (i.e., project books, STILE, final reports, questionnaire), and the researcher’ journal. See Table 3.2 for the data set. The data generation timeline is presented with the unit as experienced in Chapter 4 (see Table 4.1).

Table 3.2

Data Set and the Amount of Digital Storage

<table>
<thead>
<tr>
<th>Data Instrument</th>
<th>Amount</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video Data</td>
<td>7 lessons of two groups each lesson</td>
<td>414 GB [11 hours 30 minutes]</td>
</tr>
</tbody>
</table>
| Interviews                              | 16 student-groups
10 individual students
2 teacher                                  | 132 MB [236:51 minutes for students, 39:06 minutes for the teacher] |
| STILE (including pre- and post-tests)   | Students’ individual and group answers (including digital representations) from Modules 1–9, 11. | 89.7 MB             |
| Project Books                           | All 27 project books                | 1.32 GB            |
| Final Reports                           | All 7 group reports                 | 12.1 MB            |
| Online Questionnaires                   | 26 responses (15-minute survey of 15 questions) | 3.4 MB             |
| **TOTAL**                               | **415.3 GB**                        |                    |

The next section, data analysis, focuses on the data organisation and complexity reduction, along with a broad overview of the analyses methods and frameworks used to understand this complex data set.

3.2.4 Data analysis

This section explains the iterative and systematic process I undertook to select and analyse evidence of student learning through representations to build the case analysis (Klette, 2009). Initial data organisation informed ongoing
research and enabled me to assess the total data set. Data complexity and reduction facilitated the initial construction of lesson sequences, enabling me to better understand the research setting, justify, and build the case. Ongoing refinement continued through coarse and fine-grained analyses, integrating multiple theoretical frameworks to orient to the research focus. Concurrent to this process, I was able to conduct analyses on the more discrete data sets, such as the pre- and post-tests, interviews, and the online questionnaire, which were later integrated into the case analysis. I begin by explaining my approach to data organisation and complexity reduction, then elaborate on my application of video analysis, and outline how I addressed data quality and ethical considerations.

Data organisation and complexity reduction

The multiple method ethnography resulted in a large and complex data set. In all, the video footage, interviews, students’ artefacts, and questionnaires constituted 415 GB of digital data, with the video data comprising over 99% of this by volume. Though this was not reflective of the importance of video in interpreting the findings, this volume of data presented challenges for ongoing maintenance and storage, as well as decisions for systematic reflection and data reduction.

Organisation

Initial data organisation consisted of concurrent data review for decisions and data transfer while the investigation was underway. The emergent nature of the data generation required me to review and organise the data immediately after collection, take memos, organise documents, and prepare for the next classroom visit (e.g., select video instances and artefacts for prompts, prepare possible interview questions, follow up with students about missing or incomplete work).
The video-data were the most demanding: I reviewed the video footage within 24 hours of generation, drafted initial timelines and memos in my journal, and transferred files onto two external and encrypted hard drives. I wiped the camera memory cards weekly, as their memory capacities were reached. I transcribed and reviewed interviews within a week of their occurrence. Though I collected student’s artefacts throughout the unit, I accessed the complete set after the unit (e.g., students’ responses in STILE, questionnaire, final reports, project books).

After photographing the non-digital artefacts, I organised the entire library of artefacts by data instrument (e.g., interviews, artefacts), student, and date. This initial stage of organisation resulted in a data set that enabled me to reflect on the research while it was underway so that I could adapt my strategy, and also to identify, access, and coordinate it for the next stages of analysis. The next step involved complexity reduction, where I re-constructed lesson sequences and visualised the data set to help identify possible cases for further analysis. I address this in Chapter 4 where I outline how I developed the case.

*Use of video analysis*

Video-data played an important role in data analysis. Video accommodated a more dynamic and comprehensive analysis, immediately linking action to context (Klette, 2009). Orienting the footage through the student-group perspective provided insights into their thinking, particularly with the VSRI. Video data also provided a permanent record, allowing for multiple viewings and analysis over a longer time period, which was necessary with such a complex data set (Jewitt, 2012; Klette, 2009). In addition, video was easily shared with others throughout the research process (e.g., supervisors, participants), accommodating the subjective interpretive process of qualitative research (Denzin & Lincoln,
Along with the affordances for the overall analysis, video also contributed to my understanding of the broader context of the research setting, as well as with my more detailed micro-ethnographic account of student learning (Derry et al., 2010). Video had a role in systematic complexity reduction by orienting the construction of the initial lesson sequences to help organise, visualise, and relate the data set, subsequently leading to case selection.

From the case-based perspective, video-data played a prominent role. It provided a broad understanding of the DLE; it also provided a means to reconstruct/revise the lesson sequences to assist with the identification of salient instances of student reasoning with representations, in coordination with other data (Klette, 2009). The latter involved devising the two-step process of coarse and fine-grained analyses. To this end, video technology supported multi-theoretical analyses and holistic understanding of complex ethnographic data, allowing a concurrent view of discourse, visual representations and interactions, which are inherent features of a complex learning environment (Clarke et al., 2009; Clarke et al., 2011).

Video provided unique insight into the distributed, concurrent, and multimodal nature of the teacher’s and students’ communication approach and interactions (e.g., discourse, gestures, actions), along with a record of the nature of the representations used and created (Clarke et al., 2009; Jewitt, 2012; LeBaron, 2005). Video afforded particular access to interactional representations (e.g., gestures, role-plays), providing a deeper understanding of the action modality (Jewitt, 2012). Thus, I was able to identify a more comprehensive account of the multimodal representational practices as students moved flexibly among the distributed elements of this DLE. Throughout the unit, students created
and coordinated a rich collection of representations. Video helped identify the
discursive moves of the students as they engaged both digital and non-digital
resources (e.g., STILE, project books, scientific apparatus), along with the
representations accompanying their reasoning (e.g., dialogue, gestures, role-
plays). Throughout this process, video was not considered the primary source of
data, but a method that enabled coordination of data in context to re-construct a
dereper understanding of student learning. In conjunction with other sources of
data collection and analysis, I was able to more reliably represent or interpret the
social world (Atkinson & Delamont, 2005).

*Use of Studiocode*

Studiocode facilitated the multi-theoretical analyses in my research. The
software captured the active nature of classroom conversations and activities,
compared to other analytical software, which are better suited to textual or
pictorial data (Clarke, 2013). As I reviewed the video-footage, the software
enabled the application of codes to identify salient instances in context. The
multi-theoretical course-and fine-grained analyses required multiple passes of the
video footage, each with their own code schemes to identify relevant sequences. I
developed and refined multiple coding strategies to analyse each pass. Chapter 4
elaborates on this process, which resulted in a more in-depth understanding of
students’ interactions in this DLE. Given the volume and breadth of data
generated, along with the complexity of the analysis, my adherence to the
guidelines for data quality was critical.

*3.2.5 Data quality*

Both quantitative and qualitative research follow similar processes to
support the quality of the data. Quantitative data is concerned with issues of
validity (i.e., the instrument measured what it set out to) and reliability (i.e., consistent and accurate representation) (Teddlie & Tashakkori, 2009; Yin, 2014). Internal validity determines if conclusions are appropriate for the study, and external validity determines if they are generalisable (Jupp, 2006; Yin, 2014). Qualitative data is concerned with trustworthiness: if the data has captured the experience of participants, if the methods measured what the researcher intended, and if the measurement is consistent and accurate (Teddlie & Tashakkori, 2009). Trustworthiness requires spending time and building trust with the participants/informants in context (e.g., classroom, community, culture) and to understand the multiple perspectives (Teddlie & Tashakkori, 2009). Teddlie and Tashakkori (2009) outline the following criteria for trustworthiness: credibility, transferability, dependability, and confirmability. Credibility is achieved through observation and engagement, triangulation, peer debriefing, and member checks; it is similar to internal validity. Transferability is achieved through thick description and is similar to external validity. Dependability is achieved through audits and is similar to reliability. Confirmability is achieved through reflexivity and is similar to objectivity. If data quality is high in both quantitative and qualitative strands, then it is considered high for a multiple method study (Teddlie & Tashakkori, 2009).

I addressed data quality through specific decisions and processes undertaken before, during, and after my investigation. To begin, my research design drew from multiple methods of data generation and analyses, allowing for multiple perspectives and opportunities to privilege the voice of the participants, for a more in-depth understanding of students’ experiences (Denzin & Lincoln, 2013; Teddlie & Tashakkori, 2009). Thus, I embedded trustworthiness and
credibility in my research design. During the development of my data generation instruments (i.e., interviews, questionnaire), I drew on the literature and consulted with my supervisory team to inform the design and refine drafts to ensure the instruments addressed what they intended and were consistent (i.e., trustworthy). In addition, the questions in pre- and post-test instruments were aligned with the literature on misconceptions, specific to the respective scientific concepts. During the investigation, I spent time with the participants in the research setting, developing a rapport with them, building trust and an understanding of their perspectives. My attendance for most of the lessons, participation in some of the lessons and activities, and generation of field notes and video capture, contributed to trustworthiness and credibility. Further, my qualification as a certified professional teacher assisted with my familiarity with the research setting and my ability to develop a rapport with the students. To understand students’ perspectives, formal interviews using VSRI and artefacts provided an opportunity for students to elaborate on their thinking, and for us to move towards a consensus of understanding (Denzin & Lincoln, 2013). Most of the interviews were done with students in their pre-existing groups, however, the pre- and post-test interviews were done individually, allowing students to express their personal experiences outside their groups. Similarly, students completed the online questionnaire individually. The application of these methods supported the trustworthiness of the data.

Throughout the data generation process, I reviewed and analysed the data immediately, recording initial timelines, sequencing the lesson, writing memos and reflections (see the following section on Reflexivity), preparing follow-up questions for interviews, and adapting the research design if needed (e.g.,
conducting a questionnaire instead of a focus group). These processes supported trustworthiness and confirmability of the data (Cohen et al., 2011). After the field work, I reported the findings through thick descriptions of the context and participants’ perspectives, with claims supported through an integrated understanding of the data (i.e., crystallisation) to address transferability and credibility. In addition, I discussed my initial findings with the other researchers involved in the larger project and compared patterns with the literature, which supported the credibility of my findings.

**Reflexivity**

The process of reflexivity is an essential part of qualitative research where the research includes reflections on the research process and the decisions that are made prior to and during the course of the study. It is an additional method for trustworthiness (Jupp, 2006). These reflections may also include thoughts about the ethics of the investigation, along with any political dynamics that may influence the credibility and validity of the data and conclusions (Jupp, 2006). Reflexivity has a critical role in ethnographic research, where the researcher is so close to the informants and the data.

For my investigation, I recorded memos and reflections directly in my field notes (i.e., daily observation sheet) and reflexivity journal (two notebooks which also contained timelines, lesson sequences, notes from meetings with my supervisory team and other education researchers). This was particularly important given the additional potential intrusion of video-capture, including the decisions of which groups to follow and how the cameras might affect group behaviour (Jewitt, 2012). My journals included possible strategies for analysis, along with potential findings, conclusions, and issues for discussion.
3.2.6 Role of researcher and participants

In qualitative research, the relationship between the researcher and participants are inextricably intertwined (Denzin & Lincoln, 2013). To position the researcher in the research, Lincoln, Lynham, and Guba (2013) suggested that the researcher herself is an instrument in the process of undertaking research. The entire process is ultimately designed and interpreted by the researcher, informed by other researchers through literature, and assisted through the use of tools such as data instruments. The interactions between myself and the students became part of our collective experiences in this setting. The multiple instruments and ongoing interactions (e.g., verbal, written, action-oriented) were designed to privilege students’ voice.

As a practising teacher with expertise in the education setting but not a regular member of this school, I situated myself on the continuum of participant-observer (Angrosino, 2005; Hollan et al., 2000). On this continuum, my activities ranged from writing field notes, to assisting students with technology, to leading a class while the teacher was away (Angrosino, 2005). I believe my self-identity as an educator in conjunction with the students’ perception of me as a knowledgeable other necessitated this perception of my role. Again, the multiple instruments assisted in understanding students’ voice, along with my ongoing reflections.

As an ethnography, I had an intentional membership with this school and classroom, and became a part of the community under research, with full awareness of inevitably influencing the students’ learning and experiences (Angrosino, 2005; Pink, 2007). A positive outcome included becoming more familiar with the participants to support a more realistic and in-depth
understanding of the phenomena under study (Pink, 2007). By the first lesson, I had learned all the students’ names and greeted them as they entered the classroom each day. Conversely, the negative aspect included unduly influencing students’ agency in their learning. To address this, I embedded various provisions for accommodating students’ voice and agency (e.g., individual and group interviews, agency with the video camera). As a subjective undertaking, qualitative research does not require exclusion of bias, but an account of it. By describing my role in the research, my intention is to account for my relationship with those involved in the research, along with the context (Denzin & Lincoln, 2013).

3.2.7 Ethical considerations

This investigation involved both formal and informal ethical considerations, including an ethics clearance from Deakin University, informed consent by the school, voluntary participation by the teachers and students, confidentiality and security of information, anonymity of school and participants, and appropriate credentials of the researchers. The chief investigators for the ARC digital inquiry project had already acquired formal ethics clearance (re: Project number 2013-230). The Deakin University Human Research Ethics Committee (DUHREC) approved the ethics application for the period from 7/10/2013 to 7/10/2017. The request for modification (i.e., addition of myself as a member of the research team) was approved on August 27, 2015. Through this application process, the university, researchers, and school achieved informed consent.

Prior to undertaking the investigation, I visited the class to discuss the nature of my research and their role. At this time, the students were already aware
of my presence in the school from my research in the previous term and were aware that their science teachers were working with Deakin researchers. The teacher I worked with agreed to participate in my investigation, invited her students to participate, and coordinated the consent forms with the students and their parents. By the first day of my investigation, the classroom teacher received informed consent from all the students, each signing their own consent form.

With the use of video technology in ethnographic research, I was cognisant of how my presence, along with the GoPro camera, affected the students’ ability to maintain the kind of conversations, actions, and interactions that would normally take place otherwise (Jewitt, 2012; LeBaron, 2005). I met with the teacher first, and then with her class prior to implementing the video-capture method to minimise disruption of regular classroom practices while the investigation was underway (Denzin & Lincoln, 2011). During this initial visit, I introduced myself and described my research and some of the methods to be used, including the use of video-capture and interviews, and how each method would assist to form a better understanding of their perspective. In the following class, when I began the video-capture, the first two groups I invited to video were based on the teacher’s suggestion, as she was more familiar with her students. As the research was underway, each group had the option of declining to be videoed and interviewed, although no group exercised this option. To ensure confidentiality and security of the information, all data were encrypted and secured in a locked desk and a password-protected cloud drive. In addition, the school and participants were assigned pseudonyms. Finally, as a researcher for this investigation, I had qualification to work with children through my current
professional teaching certification in British Columbia, Canada, as well as a
current *Working with Children Check* in Victoria, Australia.

### 3.3 Chapter Summary

This chapter outlined my research focus, rationale for my research
approach, and research design, which included multiple methods to support my
ethnographic investigation. Analysis of the data generated is presented in the
following findings chapters, beginning with a more detailed account of the DLE.
Chapter 4. The Unit as Experienced

Chapter 4 presents the unit as experienced by the students, describing this DLE from their perspective. It addresses RQ1: What were the generative features of this DLE in supporting an inquiry-based RCA? I argue that this DLE provided flexibility for variations in students’ learning pathways, a high proportion of face-to-face interactions and student-to-student dialogue, and a broad range of multimodal, digital, and non-digital (i.e., multimedia) representational resources to support meaning-making processes. The first section focuses on a summary of the unit and how I constructed an overview of each lesson. The second section focuses on the unit as experienced from the theoretical perspectives of representation construction and distributed cognition. In contrast to the unit as planned (see Chapter 3), this chapter elaborates on the nature of this DLE, providing a context to the findings for in the following chapters.

4.1 Reconstructing the Unit

Using a similar strategy to the unit as planned, I re-constructed the unit and individual lessons as experienced by the students by coordinating their responses to the activities recorded in STILE and their project books, with my field notes and video footage. Table 4.1 shows the sequence of modules, description of the lessons, students’ activities, and the data generated. The modules are numbered as they appeared in STILE and are presented by chronological lesson, with the length of the lesson indicated in parenthesis. I have also indicated the specific questions addressed by the students in parenthesis (e.g., Q1 refers to Question 1). Due to scheduling constraints, I was only present from Modules 3 to 11 and used video-capture from Modules 6 to 11 (see Table 4.1).
Table 4.1

Sequence of Modules, Description of the Lesson, Activities, and Data Generated.

<table>
<thead>
<tr>
<th>Lessons and Module Number in STILE*</th>
<th>Description of Lesson</th>
<th>Activities</th>
<th>Data Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lesson 1 (75 minutes)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Introduction</td>
<td>Students completed activities as a survey of their prior knowledge.</td>
<td>1.0 Quiz: <em>What I know about Energy</em>. Students participated in a 15-question multiple choice and short answer survey of prior knowledge (Q1–15). 1.2 a) Word Cloud. Students constructed a digital word cloud about <em>Energy</em> (Q1). b) Mind map. Students constructed a digital mind map to organise the forms of energy in their everyday lives (Q2). 2.1 Live Poll: <em>My Attitudes to Climate Change</em>. Students completed a whole-class live poll to assess their attitudes on climate change (Q1–10). They compared their answers with those from a nation-wide survey.</td>
<td>Online survey of students’ learning (i.e., pre-test). Artefacts: STILE and Project Books</td>
</tr>
<tr>
<td>2. Attitudes to climate change</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lesson 2 (60 minutes)</td>
<td>Students viewed videos about climate change and sustainable housing. They constructed mind maps on greenhouse gases and passive design strategies.</td>
<td>3.1 Climate Change: Video Jigsaw Discussion. Students viewed a video, addressed questions using the Jigsaw method and shared their learning with their classmates. a) Mind map. Students constructed a mind map on greenhouse gases using a variety of evidence (e.g., video, online reports) (Q1). b) Students responded to an Australian-based document about Global Warming (Q2). c) Students constructed a text-based presentation on evidence of Climate Change in Australia (Q3). 4.1 Net Zero Energy Building Designs. Students constructed a mind map on sustainable housing based on the STILE video (Q1).</td>
<td>Artefacts: STILE and Project Books</td>
</tr>
</tbody>
</table>
| Lesson 3  
| (75 minutes)  
| 5. Temperature and thermal energy  
| Students engaged in the online activities within the module. They learned how to construct representations incorporating the particle model.  
| 5.1 Quiz: Ideas about Matter. Students completed a multiple choice survey of their prior knowledge (Q1–7).  
| 5.2 Representational Challenge: Particles in Matter. Students constructed representations depicting how particles in matter exist in six different scenarios (Q1).  
| 5.3 Representing Temperature. Using role-play as representation, students demonstrated how plasticine holds its shape at different temperatures (Q1). Students also constructed diagrams and explanations for this.  
| 5.4 Representing Particles in Matter. Students viewed a video and then represented how particles exist as solids, liquids, and gases as text and drawings (Q1).  
| 5.5 Representing Temperature, Thermal Energy, and Heat. Students viewed videos, constructed drawings, and explored related scenarios (Q1–4).  
| Classroom observations.  
| Artefacts: STILE and Project Books  

| Lesson 4  
| (60 minutes)  
| 6. Heat transfer: Conduction  
| Students reviewed key ideas about properties of matter and constructed representations showing how energy transfers in a conductor and an insulator.  
| 6.1 Representing Conduction. Students created role-plays to represent energy transfer in conductors and insulators. They viewed videos and applied their knowledge to explain different scenarios in writing and using drawn representations (Q1–2), along with answering three multiple choice questions (Q3–5).  
| Classroom observations.  
| Brief video record of 2 groups (Ina & Candace)  
| Artefacts: STILE and Project Books  

| Lesson 5  
| (75 minutes)  
| 6. Heat transfer: Conduction  
| Students learned how to use dataloggers by conducting their own temperature investigation.  
| Investigating Heating. Students oriented to the dataloggers and temperature probes by investigating the effects of temperatures on different materials. Students viewed a video to prepare for an investigation, then carried out the investigation. They made a prediction (Q1), uploaded a photo of their digitally generated temperature graph (Q3), and explained their results (Q4).  
| Classroom observations.  
| Full video record of 2 groups (Bianca & Nelli)  
| Interviews: 1 group  
| Artefacts: STILE and Project Books  


### Lesson 6 (60 minutes)

#### 7. Heat transfer: Convection

Students engaged in online activities within the module. They watched a teacher-led demonstration on convection and conducted a hands-on activity.

7.1 Understanding Convection. Students viewed a video and applied their knowledge to different scenarios: answering a text-based question about how fans work (Q1) and drawing diagrams showing convection currents in candles (Q2) and hot water heaters (Q3).

7.2 Teabag Rocket. Students viewed a video explaining the activity, completed the activity, and drew representations to explain how convection currents occurred (Q1).

**Classroom observations.**
- Full video record of 2 groups (Bianca & Haga)
- Interviews: 1 group
- Artefacts: STILE and Project Books

### Lesson 7 (75 minutes)

#### 8. Electromagnetic Radiation: What is it?

Students engaged in online activities within the module. They constructed a multimedia presentation.

8.1 Creating Radiation. Students viewed a video, drew representations to compare high and low frequency radiation (Q1), and described how radiation related to the electromagnetic spectrum (Q2).

8.2 Electromagnetic Spectrum. Students viewed a video and reviewed the electromagnetic spectrum, using the fill-in-the-blank table to guide the discussion (Q1).

8.3 Representational Challenge. Student-groups created a multimedia presentation on one type of electromagnetic radiation (Q1).

**Classroom observations.**
- Full video record of 2 groups (Ina & Nelli)
- Interviews: 2 groups
- Artefacts: STILE and Project Books

### Lesson 8 (60 minutes)

#### 9. Grand Designs episode

Students viewed a video on sustainable housing and completed the online questions for Module 8.

Students viewed this video and then participated in a brief whole-class discussion.

**Classroom observations.**
- Interviews: 2 groups plus the teacher
- Artefacts: STILE and Project Books
<table>
<thead>
<tr>
<th>Lesson 9 (75 minutes)</th>
<th>Over the next three lessons, students engaged in an inquiry to investigate passive design strategies used in sustainable houses. Students applied their understanding of sustainable housing by investigating passive design strategies.</th>
<th>11.1 Sustainable Housing Inquiry. Part 1: The teacher introduced the Sustainable Housing Inquiry and explained the assessment process while the students listened. Students chose groups and began planning their investigation.</th>
<th>Classroom observations. Video record of 2 groups (Bianca &amp; Ina). Artefacts: STILE and Project Books</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lesson 10 (60 minutes)</td>
<td>Student-groups finished planning and then conducted their experiment.</td>
<td>Part 2: The teacher reviewed the peer assessment process. Students completed the planning process, conducted their respective experiments, and completed data collection.</td>
<td>Classroom observations. Full video record of 2 groups (Haga &amp; Ina). Artefacts: STILE and Project Books</td>
</tr>
<tr>
<td>Lesson 11 (75 minutes)</td>
<td>Student-groups constructed their final report.</td>
<td>Part 3: Students drafted their final report in their respective project groups.</td>
<td>Classroom observations. Full video record of 2 groups (Haga &amp; Ina). Interviews: 3 groups Artefacts: STILE and Project Books</td>
</tr>
<tr>
<td>Post unit Data Generation (1 week after final lesson)</td>
<td>Students completed the online survey of their learning (i.e., post-test) (Q1–15). They also completed the online questionnaire about their learning experiences (Q1–15).</td>
<td>Online survey of students’ learning (i.e., post-test). Online questionnaire about students’ learning experiences.</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>12. What I know about energy</td>
<td>Students completed the online survey of their learning (i.e., post-test) (Q1–15). They also completed the online questionnaire about their learning experiences.</td>
<td>Interviews: 10 individual students. Artefacts: Final reports.</td>
<td></td>
</tr>
<tr>
<td>13. Your thoughts</td>
<td></td>
<td>Interviews: 7 groups of students</td>
<td></td>
</tr>
<tr>
<td>Post-unit Data Generation (2 weeks after final lesson)</td>
<td></td>
<td>Interview with teacher</td>
<td></td>
</tr>
<tr>
<td>Post-unit Data Generation (3 weeks after final lesson)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Modules are numbered as they appeared in STILE and presented in the same sequence that they were taught.
Compared to the unit as planned, the unit as experienced had the following adaptations:

- Module 6 took place during a planned absence by the teacher, who then invited me to lead that class to maintain a consistent pedagogical approach as well as the lesson schedule. This was the first lesson of the Conduction module.

- In Module 7, the teacher incorporated an impromptu teacher-led demonstration on convection using potassium permanganate.

- In Module 8, the students did not engage in Activities 8.4 and 8.5 due to time constraints. Activity 8.4 focused on radiation and the atmosphere, linking electromagnetic radiation and greenhouse gases. Activity 8.5 focused on the greenhouse effect, with activities elaborating on the differences between the greenhouse effect and the enhanced greenhouse effect (see Table 3.1).

- Module 9 on Visible Light and Vision was replaced by a video on Grand Designs to allow students time to complete the questions in STILE and reward them for their engagement in the unit. Grand Designs is a popular TV show in Australia and this episode featured the construction of a sustainable house. It was chosen by the teacher to provide context to the Sustainable House Inquiry task.

Other modifications were based around issues with technology, including internet connectivity, and projector and datalogger probe malfunctions. In these situations, the teacher suggested students record their activity responses in their project books and upload to STILE at a later date, view the STILE video from their personal laptops, and carry on with the investigation with a single
temperature probe. Modules 12 and 13 were completed outside of the science lesson within a week of the final Sustainable Housing Inquiry lesson. Overall, the teacher’s orchestration of the unit was mostly consistent with the embedded lesson sequence, with changes to accommodate the realities of the naturalistic classroom setting, including scheduling constraints and issues with technology. Some modifications had implications for students’ learning (e.g., the omission of Activities 8.4 and 8.5), particularly with the post-test responses. These are addressed in Chapter 7. Specific information about the activities and resources (e.g., videos) in Modules 1-8 are presented in Chapter 5.

For the questionnaire (see Appendix A), 26 of the possible 27 students responded to most of the questions. I selected responses regarding digital and non-digital technologies to provide insight into students’ experiences with these elements of the learning environment. These questions oriented around students’ use of the project books, the Paint program, Google Docs, and the datalogger (Q4–Q6, Q12). The whole-class responses are presented within relevant sections in Chapters 5 and 6 to provide the broader context of their experiences.

4.1.1 Reconstructing lessons in the unit

I reconstructed the lesson sequences using my field notes and students’ artefacts, and corroborated the sequences with the video data (i.e., footage of five different groups over six lessons). To begin, I randomly chose one of the groups’ footage. For each module, I printed out all the activities and questions, along with the groups’ responses, both online and in their project books, and assembled them into my Data Book. From this, I was able to reference these artefacts with the six videoed lesson sequences to construct: a brief synopsis of each lesson; a summary of the lesson; the accompanying data (e.g., video files, interviews, artefacts); and
the lesson plan (including time, teacher and student activity, technology, and relevant images). For example, the following summary of the Radiation lesson in Module 8 provided more detail than the synopsis in Table 4.1.

The lesson began with a student reading aloud the Key ideas from the STILE module. Students responded by generating questions about these in their project books and sharing them with the whole class. As a class, they viewed the Radiation video and applied their knowledge by representing how particles move at different frequencies using wave diagrams (Activity 8.1). Then they viewed a second video on the Electromagnetic Spectrum, and in groups, addressed the fill-in-the blank questions and reviewed their answers as a class (Activity 8.2). Finally, in pairs or groups of three, students constructed a digital multimedia representation synthesising key ideas related to radiation and the electromagnetic spectrum (Activity 8.3).

These accounts of the lessons as experienced provided context around the interactions that took place. To understand students’ experience of the representational resources, I identified and coded the salient features of this DLE.

4.1.2 Analytical perspectives of the DLE

Video-based analysis provided a more comprehensive understanding of the complexity of this DLE, with dynamic interactions among students, technologies, and multiple representations. Using Studiocode software, I reviewed the video-footage of five different student-groups in six lessons (with two different groups for each lesson). I identified three analytical perspectives to investigate the generative features: blended interactions, dialogic interactions, and the nature of representational resources (Klette, 2009). Using the combined
experiences of the two groups in each lesson provided a more in-depth understanding of features relevant to RCA and distributed cognitive systems.

My method followed a similar approach used by Klette (2009) for analysing a large corpus of video data. I identified and refined coding categories for each of the analytical perspectives, applied the codes to identify salient instances in the video, and summed the sequence of instances to determine the approximate amount of time dedicated to each category. After reviewing the corpus of video, I developed coding categories for each of the analytical perspectives. Following the focus of the research question, I distinguished the blended interactions as either face-to-face or online interactions, along with the nature of representational resources as either digital or non-digital. I incorporated theoretical coding into the dialogical interactions to distinguish student and teacher interactions. I further refined the coding categories by focusing only on matters related to science (e.g., as opposed to administrative tasks, web surfing). I then applied the codes to each video resulting in a series of timelines with a sequence of instances for each code category that could be summed to determine the approximate amount of time dedicated to that category.

In the following sections, I present and interpret the StudioCode timelines and the results of the analysis for each of the six lessons in two parts: blended interactions and distributed interactions. To simplify the presentation, I present a single group’s timeline for each of the analytical perspectives. I use Bianca’s group of three to four students for the convection and conduction lessons, and Ina’s group of three to six students for the radiation and inquiry lessons.
4.2 Part I: Blended Interactions

4.2.1 Coding for face-to-face and online interactions

Following the literature review, my research setting is described as a digital learning environment involving the blending of face-to-face and online interactions within a classroom with the teacher and students present at the same time. Because the learning sequences were embedded in the cloud-based platform, I developed codes to distinguish the interactions in each of these two domains, face-to-face and online.

The face-to-face codes focus on instances related to the teacher and students interacting with scientific ideas, information, and activities within the material environment (i.e., without needing to be online). These included dialogue, role-plays, and practical investigations. The online codes referred to interactions with scientific ideas, information, and activities that could not otherwise be accomplished unless the teacher or students were online. These included accessing and viewing videos embedded in STILE, completing STILE activities, and writing in Google Docs. These did not include writing in MS Word, or using the digital camera or dataloggers, which were addressed in the technology analysis. Coding was not sequential in nature: At times they were concurrent (e.g., when the internet was not accessible to some students they had no other option but to work offline, when different group members performed different tasks in a given activity, when group members made different choices to represent digitally or by hand). Coded instances had to be at least five seconds in duration to be counted. See Table 4.2 for the code guide.
Table 4.2

Guidelines for Applying Blended Interactions Codes

<table>
<thead>
<tr>
<th>Blended Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face-to-face: Instances related to the teacher and students interacting with scientific ideas, information, and activities within the material environment (i.e., without needing to be online).</td>
</tr>
<tr>
<td>Online: Instances related to teacher and student interactions with scientific ideas, information, and activities that could not otherwise be accomplished unless the teacher and/or students were online.</td>
</tr>
</tbody>
</table>

Figures 4.1–4.3 show the timelines and coding (i.e., online, offline, concurrent) for the six videoed lessons. Since there was no single group videoed across the six lessons, I averaged the numbers between the two videoed groups for each analysis to provide an overview of the interactions and presented the data in a table format to identify broad trends. These analyses offer an approximation of the interactions over the six lessons. Time was calculated from the respective instances in each timeline through an automated process in Studiocode, added and rounded off to the nearest second, and coordinated with the field notes for validity (Jewitt, 2012). In addition, the timelines for this analysis were organised to help distinguish patterns for the classroom lessons and the summative inquiry task. The first three timelines related to the regular instructional lessons in conduction, convection, and radiation. The remaining three timelines related to the end-of-unit Sustainable Housing (SH) Inquiry task. Though the conduction lesson was delivered in two parts (see Table 4.1), I presented the timeline for the second lesson as it included a full video account of the lesson. A brief description of the lesson precedes each of the timelines, followed by an explanation of the patterns as a result of the coding.
Blending during the instructional lessons

After learning about climate change, temperature and thermal energy, students explored conduction, convection, and radiation as the key scientific concepts to inform their SH Inquiry task (see Figures 4.1–4.3).
Figure 4.1. Bianca’s group timeline in the conduction lesson.

Figure 4.2. Bianca’s group timeline in the convection lesson.

Figure 4.3. Ina’s group timeline in the radiation lesson.
To assist with interpreting these timelines, please refer to Figure 4.1 for the following explanation: This timeline illustrates the three codes (i.e., Face-to-Face, Online, Concurrent) that were salient for this 48-minute video record. The time scale is indicated in minutes on the top horizontal axis. Instances for each code are numbered to indicate the chronological number of sequences. The total time attributed to each code is indicated in the summary tables at the end of each section (see Tables 4.3, 4.5, and 4.7).

For these three videoed lessons, face-to-face interactions were predominant, with a large amount of concurrent interactions, and a small amount of exclusive online interactions. Each lesson began with face-to-face interactions, typically consisting of the teacher performing administrative duties (though this was not coded), orienting students to the purpose of the lesson and key activities, and engaging students in an activity to review the prior topic and introduce the new topic. The radiation lesson indicated concurrent interactions as students were introduced to the topic by reading the key ideas in the module. The conduction lesson showed the most face-to-face interactions as students demonstrated their prior learning through role-play, listened to a teacher-led demonstration about dataloggers, and undertook their first practical investigation.

The following two lessons showed a more even distribution of interactions. In the convection lesson, the teacher integrated the online videos, and students participated in online activities as well as practical investigations. In the final part of the class, students had the option to work online or in their project books as a response to connectivity issues and preferences, hence the concurrent coding. These interactions were similar for the radiation lesson, where the
students viewed videos and engaged in the online activities. Figure 4.4 shows whole-class and group-based interactions.

Figure 4.4. Class viewing the video on how to do the convection investigation (left), and students constructing representations in the radiation module in STILE and in their project books (right).

The teacher orchestrated the sequencing and the pace of the online and face-to-face interactions, addressing the whole class, groups, and individual students throughout. She directed the online interactions by using phrases such as “class, open your laptops” and “please access STILE”. The teacher typically followed the modules sequentially throughout the unit and presented students with the option to create representations in STILE or in their project books, based on their preferences or connectivity issues. Students viewed videos as a whole-class activity; however, there was one occurrence where students viewed the video within their group as the classroom projector was not working.

Blending during the Sustainable Housing Inquiry task

The next series of lessons were dedicated to the SH Inquiry task. Over three lessons, students engaged in a group-based inquiry to investigate passive design strategies used in designing sustainable houses (see Figures 4.5–4.7 and Table 4.3).
Figure 4.5. Timelines in SH Inquiry planning lesson. Note that parts a) and b) are sequential.

a) Teacher introduction of the task (above).

b) Ina’s group timeline.

Figure 4.6. Ina’s group timeline in SH Inquiry experiment lesson.

Figure 4.7. Ina’s group timeline in SH Inquiry report writing lesson.
For this series of timelines, the first two lessons were predominantly face-to-face and the last lesson was concurrent. The first lesson was almost exclusively face-to-face as the teacher introduced the task and explained the assessment (Figure 4.5a) and the students began planning (Figure 4.5b). The last few minutes were spent with Ina’s group accessing Google Docs to begin organising their final report.

The following lesson showed that Ina’s group worked exclusively face-to-face as they undertook their experiment. The teacher began the lesson by reviewing the process of peer assessment and introducing the Google Docs laboratory template. Students then completed their planning, collected their materials, conducted and completed their experiment, and continued discussing their final report (Figure 4.6).

The final lesson in this series was dedicated to group-based report writing. By this point, Ina’s group decided to use Google Docs, which they accessed online so spent this last lesson drafting their report collaboratively. In this lesson, I conducted an interview with Ina’s group, hence the truncated coding for the online mode (Figure 4.7). For the entire SH Inquiry, Ina’s group did not access STILE to complete tasks or activities. They were guided primarily by handouts provided by the teacher (e.g., planning, peer assessment), followed their own experimental designs for their investigations, and drafted their reports using different digital media (e.g., Google Docs).

From the respective timelines, I determined the amount of time spent for each of the types of interactions, with the corresponding data from Bianca’s and Ina’s groups’ timelines presented as Group 1 and Group 2 respectively (see Table 4.3). Due to the inexact nature of the comparison of data across only two groups,
the broad interactional trends were calculated as approximate, comparing the two groups per lessons, with the face-to-face, online, and concurrent interactions.

Given this variation, there was no basis on which to average across lessons and groups.

Table 4.3
Comparison of Time Spent in Each Domain (in minutes) for each of the Two Groups

<table>
<thead>
<tr>
<th>Blended Interactions</th>
<th>Conduction</th>
<th>Convection</th>
<th>Radiation</th>
<th>SH Planning</th>
<th>SH Expt</th>
<th>SH Report</th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Face-to-Face</td>
<td>43</td>
<td>38</td>
<td>58</td>
<td>50</td>
<td>57</td>
<td>37</td>
<td>283</td>
</tr>
<tr>
<td>1 Online</td>
<td>3</td>
<td>28</td>
<td>51</td>
<td>7</td>
<td>0</td>
<td>37</td>
<td>126</td>
</tr>
<tr>
<td>1 Concurrent</td>
<td>1</td>
<td>13</td>
<td>47</td>
<td>1</td>
<td>0</td>
<td>37</td>
<td>98</td>
</tr>
<tr>
<td><strong>Total Videoed Time</strong></td>
<td><strong>Group 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Face-to-Face</td>
<td>35</td>
<td>43</td>
<td>57</td>
<td>48</td>
<td>59</td>
<td>67</td>
<td>308</td>
</tr>
<tr>
<td>2 Online</td>
<td>3</td>
<td>18</td>
<td>55</td>
<td>0</td>
<td>34</td>
<td>67</td>
<td>176</td>
</tr>
<tr>
<td>2 Concurrent</td>
<td>2</td>
<td>6</td>
<td>48</td>
<td>0</td>
<td>34</td>
<td>67</td>
<td>157</td>
</tr>
<tr>
<td><strong>Total Videoed Time</strong></td>
<td><strong>Group 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Overall, both groups of students spent more time participating in face-to-face interactions than those online. Each group showed variations in the time spent in each domain. During the SH inquiry, the two groups diverged where Group 2 carried out face-to-face planning, while Group 1 accessed Google Docs online. In the next lesson, Group 2 integrated the online domain (using Google Docs) during their experiment, while Group 1 did not. The groups’ response to the modules showed differences in their uptake of resources based on their personal choices. Both groups spent most of their time in the face-to-face interactions, with about a half of the time spent online, and at least 75% of this concurrent.
4.2.2 Summary of Part I

Students shifted between face-to-face and online interactions and sometimes engaged in both simultaneously. These shifts were a result of the design of the modules in the online learning platform, the teacher’s orchestration of activities, and students’ preferences. The learning sequences were carefully scaffolded in the cloud to guide students through activities, content, videos, internet links, questions and practical investigations, in both face-to-face and online domains. At times, the teacher specifically directed students to work online or in their project books, or alternatively accommodated students’ choice and connectivity issues. This analysis showed predominantly face-to-face interactions, suggesting conditions for social learning interactions were provided. The exclusive online interactions were limited, though the use of the cloud-based platform suggests the possibility for a fully blended learning pedagogy. This idea is explored in the Discussion Chapter. The next section investigates the interactions that took place through dialogue, digital, and non-digital elements that constitute the distributed cognitive system.

4.3 Part II: Distributed Social and Material Interactions

Part II focuses on how students interacted through dialogue, digital, and non-digital elements, within a distributed cognitive system. The application of the DCog framework provided insights into how students interacted among these elements. The RCA pedagogy integrated guided-inquiry and active knowledge-construction practices resulting in dynamic social and material interactions. The DLE combined the complexities of a science classroom with a digital environment, expanding the range of interactions through multimedia and multimodal resources, along with the potential of temporal and spatial dimensions.
supported through this cloud-based platform (i.e., where students could work outside the classroom in their own time) (Hutchins, 1995; Zhang & Patel, 2006).

The DCog framework organised the social and material interactions to gain insight into the affordances of this setting along with students’ strategies as they negotiated tasks (Hollan et al., 2000; Hutchins, 1995). I identified the social interactions (i.e., dialogue), and the material interactions (e.g., digital and non-digital representational resources) as key elements in this system (Zhang & Patel, 2006) (see Figure 4.8).

Figure 4.8. Distributed elements including social and material interactions.

The analysis was thus organised into social and material interactions. The first part focuses on the social interactions, specifically, the dialogic interactions between the teacher and students, elaborating on the nature of the face-to-face interactions.
4.3.1 Coding for social (i.e., dialogic) interactions

To understand the nature of face-to-face interactions, I developed theoretically informed codes to distinguish the broader patterns of students and teacher communication on matters related to science. The coding categories identified the following salient instances: the teacher interacting with the whole class (i.e., teacher-class), a specific group (i.e., teacher-group), and individual students (i.e., teacher-student) (Scott & Mortimer, 2005). Students’ dialogue included students speaking within their groups (i.e., student-student).

The student-group coding was consistent with the organisation of the classroom. That is, students were seated in groups throughout the unit, and worked as individuals and with other group members depending on the task. Because the students organised themselves into groups throughout the unit, I coded the student-student interactions as a unit of analysis, except when the teacher addressed a single individual in a given group. Coding was sometimes concurrent (e.g., when the teacher was talking to the class, and students were talking amongst themselves in groups on topic). Dialogue concerning greetings, administration, and non-science related topics were excluded as much as possible (Table 4.4).
Table 4.4

Guidelines for Applying Dialogue Codes

<table>
<thead>
<tr>
<th>Dialogue</th>
<th>Teacher: The teacher code applied to the regular classroom teacher, the teacher assistant, and the researcher, addressing students for the purpose of science instruction. This does not include dialogue related to greetings or administrative tasks.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student-Student:</td>
<td>Talking with (an)other member(s) of the group on matters related to science. Includes dialogue primarily related to scientific concepts, activities, and investigations.</td>
</tr>
<tr>
<td>Teacher addressing the whole class:</td>
<td>Includes dialogue through whole-class discussions (e.g., following an initiate-response-evaluate sequence), during demonstrations, while showing videos, giving directions, advice, and reminders.</td>
</tr>
<tr>
<td>Teacher addressing a specific group:</td>
<td>Includes dialogue between the teacher and a specific student-group (e.g., a member of Ina’s or Bianca’s group) where the teacher interacts with more than one member of the group.</td>
</tr>
<tr>
<td>Teacher addressing an individual student:</td>
<td>Includes dialogue between the teacher and a single student. If this occurs while the student is situated within her group, the other group members are not participating in the conversation.</td>
</tr>
</tbody>
</table>

Following the same method I applied in the previous analysis, I coded the same two sets of six videoed lessons as separate timelines, and presented the timelines based on the perspectives of Ina’s and Bianca’s groups (Figures 4.9–4.14). Because the cameras were placed with two groups in each of the six lessons, the teacher related dialogue is captured from the student-group perspective.

_Dialogic interactions during instructional lessons_

The instructional lessons are presented in the following three timelines (Figures 4.9–4.11) and in Table 4.5.
Figure 4.9. Bianca’s group timeline in conduction lesson.

Figure 4.10. Bianca’s group timeline in convection lesson.

Figure 4.11. Ina’s group timeline in radiation lesson.
For all three lessons, the student-student interactions were predominant, followed by the teacher-class interactions. There were fewer teacher interactions with these two groups compared to the other two whose timelines are not presented. The teacher-student interaction was limited to Bianca’s group during the conduction lesson. Some of the dialogue coding instances took place concurrently as conversations tended to be simultaneous (e.g., unlike talking over a one-way radio telephone). With up to six students in a given group, there was intermittent pair-based dialogue throughout a given activity, which was coded as student-student dialogue.

*Dialogic interactions during the Sustainable Housing Inquiry task*

The next three lessons were dedicated to the SH Inquiry task (see Figures 4.12–4.14 and Table 4.5).
Figure 4.12. Timeline in SH Inquiry planning lesson. Note that parts a) and b) are sequential.

a) Teacher introduction of the task (above).

b) Ina’s group timeline.

Figure 4.13. Ina’s group timeline in SH Inquiry experiment lesson.

Figure 4.14. Ina’s group timeline in SH Inquiry report writing lesson.
Although the teacher dialogue predominated for the first part of the planning lesson, the student interactions dominated for the second part of the lesson, and the subsequent lessons. After the initial introduction, the teacher addressed the class intermittently throughout the rest of the planning and experiment lessons, including Ina’s group. There was one instance where the teacher addressed an individual student. For the series of project-based lessons, student-student interactions were the most prominent, followed by teacher-class interactions. The corresponding data from Bianca’s and Ina’s groups’ timelines are presented as Group 1 and Group 2 respectively (see Table 4.5).

Table 4.5
Comparison of Time Spent in Each Domain (in minutes) for each of the Two Groups

<table>
<thead>
<tr>
<th>Dialogue</th>
<th>Conduction</th>
<th>Convection</th>
<th>Radiation</th>
<th>SH Planning</th>
<th>SH Expt</th>
<th>SH Report</th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Teacher-Class</td>
<td>14</td>
<td>15</td>
<td>20</td>
<td>29</td>
<td>4</td>
<td>0</td>
<td>81</td>
</tr>
<tr>
<td>1 Teacher-Group</td>
<td>9</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>1 Teacher-Student</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>1 Student-Student</td>
<td>21</td>
<td>8</td>
<td>23</td>
<td>21</td>
<td>42</td>
<td>33</td>
<td>148</td>
</tr>
<tr>
<td><strong>Total Videoed</strong></td>
<td><strong>50</strong></td>
<td><strong>59</strong></td>
<td><strong>65</strong></td>
<td><strong>58</strong></td>
<td><strong>59</strong></td>
<td><strong>37</strong></td>
<td><strong>327</strong></td>
</tr>
<tr>
<td><strong>Time Group 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Teacher-Class</td>
<td>12</td>
<td>14</td>
<td>21</td>
<td>28</td>
<td>4</td>
<td>2</td>
<td>81</td>
</tr>
<tr>
<td>2 Teacher-Group</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>2 Teacher-Student</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2 Student-Student</td>
<td>11</td>
<td>7</td>
<td>22</td>
<td>12</td>
<td>46</td>
<td>50</td>
<td>148</td>
</tr>
<tr>
<td><strong>Total Videoed</strong></td>
<td><strong>47</strong></td>
<td><strong>60</strong></td>
<td><strong>65</strong></td>
<td><strong>49</strong></td>
<td><strong>59</strong></td>
<td><strong>67</strong></td>
<td><strong>346</strong></td>
</tr>
<tr>
<td><strong>Time Group 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5 shows a pattern of increasing teacher-class dialogue over the first four lessons of the six videoed lessons, with a sudden decrease over the final two lessons as students undertook their investigations. Student-student dialogue took place over the six lessons with a dramatic increase during the SH Inquiry.
Overall, about half of the dialogue was between students, and one quarter was between the teacher and the whole class. In other words, the amount of time students spoke within their group was almost twice as much as the amount of time the teacher spent addressing the class, group, or individual combined. Discrepancies in teacher to class dialogue between the two groups were due to differences in the video footage between groups, along with some small differences in attributing codes.

4.3.2 Summary of social interactions

The overall pattern of dialogic interactions across all videoed lessons indicated predominantly student-student dialogue, followed by teacher-class dialogue. A more detailed analysis of the nature of both the teacher and students’ dialogue in the context of representation construction is addressed in the following chapters.

Teacher and student dialogue in this DLE

The predominance of student-student discourse contrasts sharply with traditional science classrooms, which are typically teacher-led with minimal input from the students (Alexander, 2006; Lemke, 1990). The role of social meaning-making processes is central to socio-cultural perspectives of learning (Vygotsky, 1962). In science education, the social construction of knowledge takes place when students construct, share, and refine their understanding through discussions, as a scientific community of practice (Vygotsky, 1978) and is fundamental to RCA (Tytler at al., 2013b). The broad patterns presented in these dialogic timelines suggest the conditions supported whole-class and group discourse, which is necessary for inquiry-based approaches (Hackling, Smith, &
Murcia, 2010) and more direct engagement in epistemic processes (Prain & Tytler, 2013).

Dialogue as an element in the distributed cognitive system

From the DCog perspective, students mediated their learning through their social and material interactions as they undertook tasks. The dialogic analysis showed a high degree of interaction between students, as well as between teacher and students, indicative of a strong social dynamic within the distributed cognitive system (Hutchins, 1995), and consistent with the role of dialogue in RCA (Tytler et al., 2013b). These social interactions took place in coordination with the material interactions.

4.3.3 Coding for material interactions

This section focuses on how students interacted with digital and non-digital technologies in this DLE. Whereas the online coding was restricted to STILE and Google Docs, the technology coding involved more digital resources. For the purpose of this research, technology is broadly understood as a tool to enable people to perform tasks more easily in their environment and considered a mediating tool for learning (Vygotsky, 1962).

For analysis, I distinguished between digital and non-digital technology, along with dialogue, as elements in a DCog system. Digital technologies included laptops (e.g., for online word processing, to access the internet, as a digital camera), the STILE platform, videos accessed from STILE, Google Docs, dataloggers, and digital cameras. Thus, the digital code includes everything the online code used in the blended analysis, in addition to other digital technologies. The non-digital technology coding included writing or drawing in project books,
using handouts, viewing or participating in demonstrations (either teacher or student-led), and using scientific apparatus during practical investigations.

Similar to the protocols used in the previous two analyses, the coding was applied to salient instances regarding matters related to science. In addition, coding was not sequential in nature; at times, the use of digital and non-digital activities was sometimes concurrent (e.g., students viewing a video while manipulating scientific apparatus, students writing data from the dataloggers into their project books). Members of a given group might have also been using different technologies for the same task. Finally, this coding framework does not include dialogue, as it was analysed using a separate coding system. See Table 4.6 for the code guide.
Table 4.6
Guidelines for Applying Technology Codes

<table>
<thead>
<tr>
<th>Digital and Non-Digital Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non-digital:</strong> Students using non-digital tools, including project books, handouts, viewing or participating in demonstrations, and practical investigations, including use of non-digital scientific apparatus. In all cases, students were focused on matters related to science.</td>
</tr>
<tr>
<td><strong>Digital:</strong> Students using digital technologies including hardware (e.g., digital camera, timers), software (e.g., MS Word, Google Docs), internet (e.g., accessing STILE, accessing information for research purposes), dataloggers, and digital camera. In all cases, students were focused on matters related to science.</td>
</tr>
</tbody>
</table>

| Project books: | Students writing or drawing in project books. |
| Handouts: | Students reading, reviewing, and referencing the handouts to complete a task. |
| Demonstration: | Teacher-led demonstrations (e.g., explanation using scientific apparatus) or student-led demonstration (e.g., role-play). |
| Model: | Teacher or students using the carton to explain specific aspects, considerations, and possibilities for the sustainable house design. |
| **Practical Investigation and other hands-on activities:** | Students participating in a practical investigation where they plan, gather relevant materials, set up their experimental design, and perform investigations. This includes transitional time where they put on their lab coats or put away their materials. This is considered non-digital as it mostly involves student manipulation of scientific apparatus and materials during their practical investigations. |
| **Laptop (other):** | Students using laptops for other purposes than STILE or accessing videos. This included using MS Office, accessing the internet for research purposes, and using the digital camera function on the detachable laptop screen. |
| STILE: | Students using the STILE platform to access or view videos (either as a group or whole-class), using the interactive canvas to construct diagrams, and using mind maps. |
| Video: | Video is always associated with STILE. It is included as a separate code to distinguish the amount of time spent viewing videos and how they are used, and also because it can also be a stand-alone resource in a classroom. |
| Google Docs: | Includes the peer assessment and lab templates accessed through Google Classroom. Note: the teacher set up Google Classroom as a way to share documents with students. Within this space, she made available the peer assessment forms used in the Inquiry project. Google Laboratory template was also accessible in Google Docs and students used this as a collaborative report-writing tool in their final report. |
| Dataloggers: | Students learning to use dataloggers and actually using dataloggers in practical investigations. Coding reflects the duration dataloggers were actively engaged for programming the settings and collecting and displaying the data. |
Similar to previous analyses, I coded two sets of the six videoed lessons as separate timelines and presented the perspectives of Bianca’s group and Ina’s group (see Figures 4.15–4.20).

Use of digital and non-digital technologies during instructional lessons

The following three lessons focused on conduction, convection, and radiation (see Figures 4.15–4.17 and Table 4.7).
Figure 4.15. Bianca’s group timeline in the conduction lesson.

Figure 4.16. Bianca’s group timeline in the convection lesson.

Figure 4.17. Ina’s group timeline in the radiation lesson.
All three lessons showed that students experienced a variety of both digital and non-digital technologies, separately, and concurrently, with STILE and project books being the most accessed. Regarding the use of digital technologies in the conduction lesson, Bianca’s group used dataloggers the most, followed by STILE, video, and laptops (for purposes other than STILE or viewing videos). For non-digital technologies, they spent most of their time participating in a practical investigation, followed by using their project books, and doing a role-play demonstration. During the practical investigation, they used the datalogger, accessing both domains concurrently.

Bianca’s group followed similar patterns in the convection lesson. For digital technologies, the group spent most of their time working in STILE, viewing videos, and using their laptops. For non-digital technologies, they spent most of their time participating in a practical investigation and using their project books. Their practical investigation took place without digital technology. For the final 10 minutes of the class, Bianca’s group was either working in STILE (if they had internet access) or in their project books. Of the three lessons, the radiation lesson consisted mostly of digital interactions. At the beginning of the lesson, Ina’s group accessed activities directly from the STILE platform (e.g., videos, questions); for the rest of the lesson, they accessed the internet and the digital media of their choice to construct a presentation about radiation.

Using technologies during the Sustainable Housing inquiry

The following series of lessons were dedicated to the SH Inquiry task (Figures 4.18–4.20).
Figure 4.18. Timelines in SH Inquiry planning lesson. Note that parts a) and b) are sequential.

a) Teacher introduction of the task (above).

b) Ina’s group timeline.

Figure 4.19. Ina’s group timeline in SH Inquiry experiment lesson.

Figure 4.20. Ina’s group timeline in SH Inquiry report writing lesson.
Similar to the patterns from the face-to-face codes, there were predominantly non-digital interactions in the planning lessons, with increasing digital interaction for the other two lessons. The handouts and model house featured prominently in the planning lesson, and for the last 10 minutes, Ina’s group accessed Google Docs. During the experiment, Ina’s group coordinated both technologies, relying mostly on the datalogger and the project book. For the last lesson, Ina’s group worked side-by-side using their lab template in Google Docs to draft their final report. This lesson was cut short because of the VSRI that took place. From these six timelines, I determined the amount of time spent using digital and non-digital technologies and constructed a table to compare this across the lessons, with the corresponding data from Bianca’s and Ina’s groups’ timelines presented as Group 1 and Group 2 respectively (see Table 4.7).
Table 4.7

Comparison of Time Spent in Each Domain (in minutes) for each of the Two Groups

<table>
<thead>
<tr>
<th></th>
<th>Group 1</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conduction</td>
<td>Convection</td>
<td>Radiation</td>
<td>SH Planning</td>
<td>SH Expt</td>
<td>SH Report</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Digital</td>
<td>40</td>
<td>32</td>
<td>80</td>
<td>9</td>
<td>40</td>
<td>37</td>
<td>238</td>
<td></td>
</tr>
<tr>
<td>Total Non-Digital</td>
<td>29</td>
<td>19</td>
<td>25</td>
<td>20</td>
<td>53</td>
<td>2</td>
<td>148</td>
<td></td>
</tr>
<tr>
<td>Concurrent</td>
<td>28</td>
<td>11</td>
<td>12</td>
<td>8</td>
<td>39</td>
<td>37</td>
<td>135</td>
<td></td>
</tr>
<tr>
<td>Total Videoed Time</td>
<td>50</td>
<td>59</td>
<td>65</td>
<td>49</td>
<td>59</td>
<td>67</td>
<td>348</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Group 2</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conduction</td>
<td>Convection</td>
<td>Radiation</td>
<td>SH Planning</td>
<td>SH Expt</td>
<td>SH Report</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Digital</td>
<td>32</td>
<td>22</td>
<td>76</td>
<td>22</td>
<td>64</td>
<td>64</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td>Total Non-Digital</td>
<td>41</td>
<td>10</td>
<td>7</td>
<td>76</td>
<td>61</td>
<td>75</td>
<td>270</td>
<td></td>
</tr>
<tr>
<td>Concurrent</td>
<td>22</td>
<td>1</td>
<td>25</td>
<td>13</td>
<td>49</td>
<td>67</td>
<td>176</td>
<td></td>
</tr>
<tr>
<td>Total Videoed Time</td>
<td>47</td>
<td>60</td>
<td>65</td>
<td>49</td>
<td>59</td>
<td>67</td>
<td>346</td>
<td></td>
</tr>
</tbody>
</table>

Over the entire unit, students experienced both digital and non-digital technologies almost equally, and in both groups concurrently almost half of the time. The first three lessons involved almost twice as much digital technology, whereas the last three lessons involved almost a third more non-digital technology. In the last three lessons, the practical investigation codes were applied for the duration of the last three lessons, except for prolonged instances where the student were not engaging with the task. That the students accessed both media separately and concurrently to construct meaning and complete tasks, particularly their project books, STILE and Google Docs, was indicative of the flexible nature of this DLE.

*Technology as an element in the distributed cognitive system*

Consideration of the social and material interactions of this distributed cognitive system provided insight into students’ experience of the complex and interconnected nature of the DLE. The timelines provided evidence of the varied
and concurrent interactions in both digital and non-digital domains with dialogue taking place throughout. Combined, they indicate variations in students’ experience of the DLE.

The variations in the timelines suggests different learning pathways for constructing meaning as students used different representational resources to complete the same task. To support this variation requires consistent access to the cloud, the ability of teachers to orchestrate cohesive learning sequences involving both domains, and for teachers and students to productively use digital technology for learning. Students were able to flexibly move between the domains or used them concurrently to complete the tasks, indicating a varied experience with multimedia representational resources for meaning-making processes. The impact of this flexibility in supporting RCA is addressed in the following chapters. The interactions with various technologies were also part of the learning, as students learned the skill of reasoning with representations and using technologies to coordinate and construct representations (Hutchins, 1998). The following chapters focus on the responses of one group, using evidence from their dialogue and student-generated representations to gain an understanding of the nature of their representations and learning.

Multimodality and RCA

The representational resources (e.g., representational forms, modes, tools) provided specific affordances for meaning-making processes. I identified the following modes as pertinent to this classroom setting: verbal, written, visual, and action. Because the spoken and written word are predominant in a science classroom, I considered these as separate linguistic modes, along with the visual and actional modes (Bezemer & Kress, 2016; Kress & Jewitt, 2003).
Following socio-semiotic perspectives, each mode is considered a meaning-making system and meaning is distributed across modes (though not necessarily evenly) (Bezemer & Kress, 2016). Multimodal representations convey meaning where each mode offers partial access to the combined meaning across modes. Each mode is potentially equally important for meaning and communication, though certain modes are better suited for certain meanings and tasks, whereas others are more suited for specific combinations or sequences. Thus, meaning is constructed in ways that are influenced through the resources provided in a given environment and through specific social interactions (Bezemer & Kress, 2016; Lemke, 1998b, 1998c).

This social semiotic perspective is increasingly drawn upon to inform contemporary science education. Traditional science classes rely heavily on the spoken and written modes, which are too limiting for the conceptually-rich nature of science (Lemke, 1998a). To understand a concept requires the use of multiple modes that are reflective of the science community and are typically integrated by language (Lemke, 2002; Bezemer & Kress, 2016; Waldrip et al., 2010). Thus, the diversity of representational resources influences the meaning-making potential in a given setting.

Digital and non-digital representational resources provided similar and different affordances to the tasks. Both supported tasks requiring the use of written language, diagrams, mind maps, and data tables. The digital mode exclusively supported student-generated word clouds, Google Slides (i.e., PowerPoint presentations), datalogger tables and graphs, digital photographs, and Google Docs. Non-digital modes exclusively supported spoken language, gestures, role-plays, student-led demonstrations, models, and student
manipulation of scientific apparatus during their practical investigations. The digital environment expanded the range of interactions, through multimedia and multimodal resources used within the culturally mediated practices of meaning making within a science classroom (Gomez, Schieble, Curwood, & Hassett, 2010; Bezemer & Kress, 2016). An analysis of the affordances of these multimodal representations in supporting meaning-making processes is addressed in the following chapters. The range of representational resources is addressed in the next section.

**Expert and student-generated representations**

This section provides a review of the representational resources experienced in the unit, included those generated by experts (e.g., canonical content provided in STILE or the teacher) as EGRs, and by the student (e.g., mind maps, drawings) as SGRs. Table 4.8 shows the variety of expert-generated and student-generated representations in the unit.
Table 4.8

List of Digital and Non-digital Representations Students Accessed and Generated During the Unit

<table>
<thead>
<tr>
<th>Representations</th>
<th>Expert-generated (EGRs)</th>
<th>Student-generated (SGRs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital</td>
<td>Written language (text and symbols)</td>
<td>Written language (text and symbols)</td>
</tr>
<tr>
<td></td>
<td>Diagrams (by digital means)</td>
<td>Diagrams (by digital means)</td>
</tr>
<tr>
<td></td>
<td>Digital photographs</td>
<td>Annotated diagrams (by digital means)</td>
</tr>
<tr>
<td></td>
<td>Videos</td>
<td>Digital word clouds</td>
</tr>
<tr>
<td></td>
<td>Google Slides/PowerPoint</td>
<td>Digital mind maps</td>
</tr>
<tr>
<td></td>
<td>Google Docs/Lab template</td>
<td>Datalogger tables</td>
</tr>
<tr>
<td>Non-digital</td>
<td>Spoken language</td>
<td>Datalogger graphs</td>
</tr>
<tr>
<td></td>
<td>Written language (text and symbols)</td>
<td>Digital photographs</td>
</tr>
<tr>
<td></td>
<td>Gestures</td>
<td>Google Slides/PowerPoint</td>
</tr>
<tr>
<td></td>
<td>Diagrams (hand-drawn)</td>
<td>Google Docs/Lab template</td>
</tr>
<tr>
<td></td>
<td>Demonstrations (Teacher-led)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Practical investigations (heating; teabag rocket)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spoken language</td>
<td>Spoken language</td>
</tr>
<tr>
<td></td>
<td>Gestures</td>
<td>Gestures</td>
</tr>
<tr>
<td></td>
<td>Written language (text and symbols)</td>
<td>Written language (text and symbols)</td>
</tr>
<tr>
<td></td>
<td>Diagrams (hand-drawn)</td>
<td>Diagrams (hand-drawn)</td>
</tr>
<tr>
<td></td>
<td>Annotated diagrams (hand-drawn)</td>
<td>Annotated diagrams (hand-drawn)</td>
</tr>
<tr>
<td></td>
<td>Role-play</td>
<td>Role-play</td>
</tr>
<tr>
<td></td>
<td>Demonstrations (Student-led)</td>
<td>Demonstrations (Student-led)</td>
</tr>
<tr>
<td></td>
<td>Practical investigations (SH Inquiry task)</td>
<td>Practical investigations (SH Inquiry task)</td>
</tr>
<tr>
<td></td>
<td>Models (SH Inquiry task)</td>
<td>Models (SH Inquiry task)</td>
</tr>
<tr>
<td></td>
<td>Mind maps (hand-drawn)</td>
<td>Mind maps (hand-drawn)</td>
</tr>
<tr>
<td></td>
<td>Data tables (hand-drawn)</td>
<td>Data tables (hand-drawn)</td>
</tr>
</tbody>
</table>

Table 4.8 illustrates the variety of digital and non-digital representations in this unit *as experienced*. Students generated written language, diagrams, annotated diagrams, and mind maps using both digital and non-digital elements. Datalogger tables and graphs were generated during students’ investigations (i.e., not pre-constructed) and were thus considered student-generated, as well as digital. Students also generated word clouds and Google Slides using digital technologies. Spoken language, gestures, demonstrations, and role-play were considered non-digital technologies and could be experienced concurrently. Broadly, students were able to generate similar representations within both elements, along with ones that were exclusive to each element. The coordination
of EGRs and SGRs is an important process in RCA and is addressed in the following chapters.

**4.4 Chapter Summary**

The purpose of this chapter was to elaborate on the nature of this DLE as experienced by students. The video-based analysis provided insights into students’ experience of blending, their dialogic interactions, and the representational resources in this DLE. Variation of students’ experiences of face-to-face and online interactions, dialogue, and technologies across the six modules and within their groups was reflective of responses to a flexible and more open-ended approach to teaching and learning. The patterns were likely attributed to the design of the learning sequences within the online learning platform, the nature of the activities, teacher orchestration of activities, and student choice of media, and available and preferred representational resources. These variations supported flexibility in students’ learning pathways (Bidarra & Rusman, 2017; Horn & Fisher, 2017; Patrick et al., 2013; Longo, 2016).

The blended and dialogue timelines showed a predominance of face-to-face interactions as well as student-to-student dialogue. This combination provided evidence that contrasted with traditional or transmissive science classrooms, which are typically teacher-led with minimal input from the students (Alexander, 2006; Lemke, 1990). These broad patterns suggested that students had a more active and collaborative role in learning science, consistent with inquiry-based approaches (Garrison & Kanata, 2004; Hackling, Smith, & Murcia, 2010; Longo, 2016). These patterns were also consistent with socio-cultural perspectives supporting the mediating role of language (Vygotsky, 1962) and the epistemic practices of science (Vygotsky, 1978), which are both central to RCA.
Finally, the face-to-face interactions were also consistent with the practices of establishing potential community collaboration (Wendt & Rockinson-Szapkiw, 2014), suggestive that this DLE provided conditions that support these epistemic practices.

The variations and implications of student choice continued through their experiences of technologies and modes. The technology timelines showed students accessing both digital and non-digital technologies almost equally, and often concurrently, indicative of the role of inquiry in enabling student choice of a range of semiotic resources to construct their own learning pathways (Longo, 2016). Students experienced digital technology almost twice as much during the instructional lessons, suggesting an important role for digital technology in supporting conceptual development through SGRs, along with the variety of tools provided by the online learning platform. Students also generated exclusively non-digital representations (e.g., gestures, role-plays, demonstrations, models) to support meaning-making processes, suggesting an important role for face-to-face interactions. In either medium, students generated text, diagrams, mind maps, and data tables, suggestive of an expanded role for cloud-based activities. Of all technologies, students experienced practical investigations, STILE, project books, and Google Docs most frequently, suggesting a viable role for both traditional and digital elements in a blended classroom. A detailed analysis of the SGRs and student learning is addressed in the following chapters.

4.4.1 The distributed cognitive perspective

The distributed cognitive perspective provided a lens by which to focus and relate the social and material interactions within this complex learning environment. The level of dialogic interactions was consistent with a DCog
system, where language is central to the task and considered both as representation and a mediator through artifacts (Hutchins, 1995).

The variety of pathways for approaching tasks and solving problems was also consistent with a DCog system, potentially supporting a diversity of representations and interpretations (Hutchins, 1995). These distributed and varied interactions were supported by the guided-inquiry approach, enabling student’s choice of learning modalities and pathways, resulting in a greater distribution of control over knowledge. This level of variation contrasts with the “one teacher, one textbook, one pathway” approach (Patrick et al., 2013, p. 9). The timelines showed a distribution of interactions among teacher, students, and multimedia resources (e.g., tools, representations, semiotic resources of both digital and non-digital nature) with no central locus of knowledge (Hutchins, 2014). Coupled to the science learning environment, these interactions presented a more authentic experience of the disciplinary-specific practices of knowledge construction (Gomez et al., 2010).

Although the analysis of these timelines does not specify cognition or learning, it does indicate that the conditions for interactions were distributed across participants and multiple semiotic resources, rather than inside the head of a single participant (Gomez et al., 2010). The findings suggest that the DLE provided conditions for collaborative, flexible, and multimodal meaning-making experiences, resulting in multiple learning pathways. The following chapters explore these interactions in depth, providing more insight into the generative features of this DLE.
Chapter 5. Students’ Experience Across the Modules

Chapter 5 builds on the unit *as experienced*, focusing on the nature of students’ responses to the learning sequences presented in Modules 1–8. It addresses RQ1: *What were the generative features of this DLE in supporting an inquiry-based RCA?*; and RQ4: *What are the implications for the design of digitally-based RCA units?* I argue that the learning environment provided flexible and expanded delivery of representational resources that supported many aspects of the RCA, but with some important omissions. As a result, students demonstrated a promising though ultimately limited ability to engage in active knowledge building processes.

The analysis followed the socio-semiotic perspective, where meaning making is supported through social interactions with representations, tools, and modes in a cultural context (Kress, 2010; Prain & Tytler, 2012). Students’ ability to construct and negotiate meaning through multimodal representations is central to developing their conceptual understanding in science and is seen as a core disciplinary practice (Lemke, 2004; Tytler et al., 2006). As such, their responses to the tasks are indicative of their conceptual development. To explore conceptual and representational development, I draw on the experiences of a single case group of three students across the conceptual modules. A formal assessment of their learning follows later in Chapter 7. To begin, I describe how I developed this case perspective of the unit.

5.1 Developing a Case Perspective of the Unit – as Experienced

To reduce the complexity of my data and focus my analysis, I reviewed the data generated to reconstruct each of the lessons and identify the main groups of students and their output (e.g., representations, interviews). I identified groups
with the most complete data sets across the modules and the strongest capacity to
verbalise their reasoning with one another (Furberg et al., 2013), and settled on a
case group of three students, Ina, Megan and Clara. This group provided
comprehensive data on both individual and group learning, the most complete
video record of the summative inquiry task, and indicated one of the biggest
learning gains in the pre- and post-test results.

5.2 Understanding Prior Knowledge and Establishing the Context (Modules
1–4)

The unit had a clear conceptual focus and was sequenced through the
online learning platform. It featured instructional resources, including content,
activities, and embedded assessment. The first four modules were designed to
elicit students’ prior knowledge about energy transfer and establish sustainable
housing and climate change as contexts for learning. Due to scheduling
constraints, I was not present for these initial lessons so evidence of student
learning only included the online instructional resources and students’ static
representations (see Section 4.1). Though students’ representations were not
formally assessed for these four modules, I provide some broad comparisons
between their responses. I begin by outlining the conceptual focus of the unit.

5.2.1 Conceptual focus of the unit

The Introduction module presented Key ideas for the entire unit. Each of
the remaining modules also featured Key ideas, with Modules 2–4 focusing on
climate change and sustainable housing, and Modules 5–8 focusing specifically
on energy transfer through conduction, convection, and radiation (see Table 5.1).
Table 5.1

The Key ideas embedded in each the Introduction, Climate Change, and Energy Transfer Modules Respectively

<table>
<thead>
<tr>
<th>Introduction to the Unit</th>
<th>Climate Change (Module 3)</th>
<th>Energy Transfer (Module 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key ideas: Energy transfer through different media can be explained using wave and particle ideas; A knowledge of energy transfer involving energies associated with light and thermal energy inform the best practices associated with the use and transfer of energy in sustainable houses.</td>
<td>Key ideas: Climate change is happening. The environment is changing: Average global temperatures are rising; Carbon dioxide levels are increasing in the atmosphere; Extreme weather events are more prevalent; Polar icecaps are diminishing.</td>
<td>Key ideas: The temperature of an object is related to the average kinetic energy of the particles that make up the object; The thermal energy of an object relates to the total kinetic energy (movement) and the energy of the particles that make up the object; Heat is the energy that gets transferred from hot objects to cooler objects.</td>
</tr>
</tbody>
</table>

The Key ideas provided a conceptual focus for the activities and final summative assessment task. The pre-test in the Introduction module included a conceptual focus informed by the literature on conceptual learning and students’ alternative conceptions.

5.2.2 Understanding students’ prior knowledge (Module 1)

The first three activities in this module elicited students’ prior knowledge about Energy. The first task was a digital survey with 15 multiple choice and short-answer questions. The multiple choice items were sourced from the AAAS (2018) website, focusing specifically on concepts and common alternative conceptions related to energy transfer through conduction, convection, and radiation, as well as climate change. Whereas the multiple choice questions
presented a text-based probe of students’ ideas, the short-answer items allowed them to express their ideas in other forms (e.g., diagrams, annotated diagrams) through the interactive canvas in STILE. The same questions were also used during the post-test as a summative assessment of their learning. An assessment of students’ responses is provided in Chapter 7.

The next activity assessed students’ prior knowledge through word clouds, using a digital application external to STILE, which were then uploaded to STILE (see Figure 5.1).

Figure 5.1. Energy word clouds constructed by Ina (above) and Clara (below).
Students then elaborated on their ideas about energy using a mind map, an application within the STILE platform (see Figure 5.2).

Figure 5.2. Energy mind maps constructed by Ina (above) and Megan (below).
Both tasks enabled students to express their ideas through a visuo-spatial organisation of text using digital media. Each representational form had different affordances: the word cloud enabled students to identify key terms related to energy, whereas the mind maps required students to condense, organise, and relate their ideas (Kress & Jewitt, 2003). As a diagnostic activity, Ina’s response indicated a more in-depth understanding of energy and engagement with the task.

5.2.3 Establishing the context (Modules 2–4)

The following three modules were designed to establish the relevant socio-scientific context of climate change and sustainable housing to engage students’ interests. A whole-class interactive survey using the live poll revealed students’ attitudes toward climate change. The live poll generated a visual display of their responses for each item in real-time, prompting a whole-class discussion (Module 2). The questions were based on a 2012 CSIRO survey involving 5,000 Australians. It provided a relevant context for the students and a basis from which to compare ideas. It also provided an account of students’ perceptions, engaging aspects of their knowledge outside a propositional knowledge focus on facts (Klein, 2006; Tytler et al., 2013b). Of the class of 27 students, 23 students agreed that climate change is happening, 21 attributed it to human activity, and 21 were either somewhat or very worried, suggesting that the students had an interest in this topic.

The activities in Module 3 provided students with canonical information about climate change. Students viewed an internet-sourced video presenting evidence for climate change. In groups, they participated in a jigsaw activity, which involved each group summarizing a specific theme in the video, then sharing their ideas with the class. The next activity provided information about
greenhouse gases through a video and online reports. Students used these resources to address related questions in STILE and to construct their second mind map, using the terms provided: greenhouse gas, carbon dioxide, nitrous oxide, and methane (see Figure 5.3).

Figure 5.3. Mind maps on Greenhouse Gases constructed by Clara (above) and Megan (below).
The contrast between students’ responses suggested the need for more discussion around greenhouse gases or instruction on how to use the mind map application. The final module in this series focused on key attributes of sustainable housing (Module 4). After viewing an internet-sourced video on Net Zero Energy Building Designs, students incorporated the key concepts in their mind map on “Sustainable Housing” (see Figure 5.4).
Figure 5.4. Mind maps on Sustainable Housing constructed by Clara (above) and Megan (below).
The third and final mind map indicated consistent patterns, with Megan providing only a minimal response. Whereas the first module focused on assessing students’ prior knowledge about energy across the unit, the subsequent three modules established the context of climate change and sustainable housing, setting the foundation for the following modules.

Modules 3 and 4 also presented canonical information about climate change and sustainable housing, followed by representational activities (i.e., mind maps) that enabled students to spatially organise this new information in a manner meaningful to them. The translation of information from the preceding videos (i.e., an expert-generated representation or EGR) to a student-generated representation (SGR) allowed students to re-represent, revise, and refine their understanding in related contexts, through EGR-SGR interplay (Tytler, Hubber, & Prain, 2013).

5.3 Engaging with the Concepts (Modules 5-8)

The following four modules were designed to develop students’ conceptual understanding of energy transfer via conduction, convection, and radiation through particle ideas using RCA. I present students’ responses to the learning sequences and compare them with the expected criteria. I provide a more comprehensive account of their learning in Chapter 7.

5.3.1 Module 5: Temperature and thermal energy

Module 5 presented the first representational challenge, where students generated particle representations. Representational challenges are open-ended conceptually-focused tasks that require students’ coordination or synthesis of multimodal representations to explain phenomena and make claims (Tytler et al., 2013a). During the lesson, I was present but with no video available, thus my
analysis of students’ learning was based on the online instructional resources and their static representations (e.g., text-based responses, diagrams).

*Assessing students’ prior knowledge (Activity 5.1)*

The module began with a digital true and false survey to explore students’ ideas about matter (see Appendix B for the survey results). The average score for the class was 41% with members in the case group scoring 28.5%, suggesting limited understanding of basic ideas about the particle model. To demonstrate the path of conceptual development through this module, I chose a single concept from the survey and followed students’ understanding of it through relevant activities: *molecules in solids are stationary* (Q5). Sixty-two percent of the students, including Ina and Clara answered “true”, suggesting an alternative conception about particle motion and thermal energy.

*Induction to SGRs with particle ideas (Activity 5.2)*

In this activity, students were presented with a series of representational challenges where they applied the particle model to demonstrate the following properties of matter through a multimodal SGRs:

1. A lump of plasticine that holds it shape.
2. A lump of plasticine that can be changed into a different shape.
3. A piece of chalk that can’t change its shape and breaks easily (brittle).
4. A rubber band can stretch and return to its original shape.
5. Red cordial and water mix easily.
6. An iron cube is much heavier than an aluminum cube of the same size.
The online question included a detailed explanation along with examples of possible representations (see Figure 5.5).

Scientists use particle ideas to explain what they observe about matter. The task below asks you to imagine and draw particles that will explain the property of the object that is given.

For example, the first challenge asks you to represent how a lump of plasticine can hold its shape. There are three examples that students have drawn below.

We need to evaluate each representation in terms of whether they can explain that the plasticine is made of particles and that it can hold its shape. This will mean that the representation needs to show particles as well as representing that the particles are connected in some way.

Representation A shows particles but doesn’t show them connected in any way. Therefore, this is not a useful representation.

Representations B & C show particles as well as being connected. Therefore, each of these representations are useful in explaining that a lump of plasticine is made of particles that holds its shape.

Figure 5.5. Activity 5.2 instructions for the representational challenge.

Students were given the option to construct their representations in their project books or use the interactive canvas in STILE. Although the class responded using either media, all three students in the case group chose to use the interactive canvas for this task (see Figure 5.6).
Figure 5.6. The case group’s responses to the six representational challenges.
In response to these six challenges, the case group generated a variety of particle representations using different features of the interactive canvas in STILE. The canvas included *sketchpad* tools (e.g., pen, shapes, lines, text, image, colour) accessed by most students through their laptop cursor and trackpad, as the laptop pens were not reliable. Within the group, there were some similarities in their representations (e.g., six discrete palettes of diagrams, colour, annotations).

For Challenge 1 and Challenge 2, each diagram needed to depict particles and their connectedness. For Challenge 2, the students might draw a before and after diagram to show that the bonds remain intact, but arrangement of particles change. All three students depicted particles and connectedness, showing a change between the two, with Megan relating the two representations using an arrow.

For Challenge 3, the bonds needed to depict a fragility or weakness (e.g., change in colour, line thickness, broken lines). Clara addressed this by adding boldface to her drawing and Ina and Megan drew the actual break. For Challenge 4, the particles should have remained the same while the bonds stretched; Ina and Megan were able to depict these features. For Challenge 5, students needed to show the mixing of the water and cordial particles. All three students illustrated these ideas, with Ina and Clara introducing the use of colour, and Megan using arrows to show the mixing of particles. Finally, for Challenge 6, students needed to depict either more or larger particles to show a difference. All students generated a pair of diagrams, with Ina and Megan using annotations.

The other 20 class responses also presented a variety of representations. Students followed similar patterns to the case group, depicting circular and connected particles, with unique variations. Some students used colour throughout
(six students) with about half of the class using colour for Challenge 5. About half of the students used annotations for Challenge 6, and a few students included more extensive annotations and explanations (seven students), integrating the textual mode. Though the case group chose to construct their representations digitally, almost half of the students constructed representations in their project books (eight students), with equivalent variation and quality. Figures 5.7 and 5.8 exemplify the variation of SGRs among the class, from single diagrams, to multimodal depictions integrating the textual mode, to relating two diagrams. These examples demonstrated how students were able to generate representations that addressed the required phenomena using similar constructive resources (e.g., colour, symbols) in both digital and non-digital media.
Figure 5.7. Class variations of representations of a lump of plasticine that can be changed into a different shape (i.e., Q2).
Figure 5.7 shows five examples of digital and non-digital representations. The first four were single diagrams featuring circular particles and connectedness. The top two were digital and depicted the bonds as spirals, implicating a degree of flexibility in the bonding. The middle two were non-digital and included text and diagrams, with one indicating that the “bonds are not strong”. The bottom diagram was the only example of the third option ‘C’ (as indicated in the instructions in Figure 5.5) and the only one that indicated movement, which was not required in this activity.

Figure 5.8 shows examples where students drew pairs of representations to illustrate a distinct change in the plasticine. The first row shows how particle connections were represented using either spirals or straight lines, with the corresponding diagrams depicting changes in shape. The second row shows the contrast of a submicroscopic and a macroscopic view of the plasticine, with annotations. The bottom row shows changes in the bonding, with annotations.
Figure 5.8. Class variations of representations of a lump of plasticine that can be changed into a different shape (i.e., Q2).
The responses to this representational challenge presented evidence of students’ varying ability to express sophisticated scientific ideas through digital and non-digital diagrams. The results supported diSessa’s (2004) claim that students have a natural ability to generate representations, and with guidance are able to represent abstract particle ideas. Students exercised choice in where and how to represent their ideas, using the digital (i.e., interactive canvas) or non-digital media (i.e., project books); they incorporated attributes such as text, diagrams, symbols, and colour. Despite working in groups, there was enough variation to show individual engagement with the task (e.g., degree of conceptual understanding, use of constructive resources, choice of media). After completing these challenges, students formed groups to enact a role-play similar to Q1 and Q2.

*From static to dynamic representations: Translation across modes (Activity 5.3)*

Thus far, students generated only static representations, using textual and visual modes, sometimes relating the two. In Activity 5.3, students generated their first dynamic representation in the form of role-play (i.e., actional mode). Students were asked to “incorporate particles ideas, using their bodies, into two scenarios: a lump of plasticine that holds its shape, and then one that holds it shape at 20°C.” The case group worked within a larger group of six and wrote their reflections individually in STILE. They demonstrated their understanding of particle connectedness through linked arms, with movement and bouncing taking place only in the second scenario. Ina’s response was indicative of her group’s ideas:

For the first challenge we (as particles) stayed still and linked our arms to show that our bonds were connected to show that we were still a lump of
plasticine. For the second challenge we stayed linked together, but bounced and moved around, to show the plasticine being heated to 20 degrees.

The modal affordance of the role-play was the focus of attention on the spatial relation between students’ bodies, the limitation of movement and connectedness through linking together, suggesting vibration as a viable option. The role-play provided specific insight into the case group’s understanding of particle motion: They exhibited only a partial understanding of particle ideas in solids, omitting the idea of movement, an idea consistent with their Activity 5.1 (Q5) response about stationary solid molecules. Activity 5.3 was the first time the Written Response application was used in the conceptual modules. This application provided an infinitely expanded ruled pad to accommodate an unlimited amount of text-based responses. After this activity, students were introduced to the canonical ideas about the particle model.

*Introducing canonical content about particle ideas (Activity 5.4)*

The initial activities in this module focused on exploring students’ prior knowledge across representations and modes. About half-way through the lesson, the class viewed a narrated video with animations of particles of substances in different states as their first introduction to canonical information. The purpose-made 45-second video was created by one of the chief investigators in this project and featured animations of particles moving in each of the states of matter (see Figure 5.9).
Students then addressed their second representational challenge: “To describe the motion of the particles that represent each state in words and then draw visual representations.” Ina provided a written response, whereas Megan and Clara provided both written explanations and diagrams (see Figure 5.10).
### Movement of atoms in the 3 states of matter

**Solid**

The particles are stuck very close to each other in a clump, and move in very small motions, almost rubbing against each other, without a big range of motion, but still stay very close together almost with a “buzzing” motion.

**Liquid**

The particles are less close together than in a solid form. The particles move more freely, and move with a bigger range of motion than the particles in a solid form. The particles move much more and with more motion. The particles are also more crowded together, than orderly.

**Gas**

The particles in a gas, are very spread apart and move very freely. They move very quickly and appear to bounce off each other—but do not touch the other particles around that except for that.

---

**Megan**

[Image of Megan's drawing showing the states of matter with labels: Solid, Liquid, Gas]

**Clara**

[Image of Clara's diagram showing the states of matter with labels: Solid, Liquid, Gas]

---

Figure 5.10. The case group’s response to representational challenge 5.4.
From EGR to SGR: Students re-represent their understanding

In response to the question posed in the video, students re-represented their ideas about matter as text and diagrams as an EGR-SGR interplay, integrating their ideas about particle movement in matter using both media. The constraint in constructing a 2D static image is to represent movement; however, all students included the idea of motion for all three states, signifying a shift from their ideas about solids as stationary expressed in their role-play and the 5.1 survey (Q5).

Summative assessment: Applying ideas in other contexts (Activity 5.5)

Building on the ideas of particle connectedness and motion, the final task allowed students to express their understanding in different representational forms and modes. The activity began with the second purpose-made video explaining each of the scientific terms: Kinetic Energy, Temperature, Thermal energy, and Heat. The use of everyday images along with animations of submicroscopic processes of particle ideas provided a context for each of the formal definitions, presenting a multimodal instructional resource for students (see Figure 5.11).
This video also contained the same image presented in Q8 in the pre- and post-tests, providing information about heat and related it to the iron-rod scenario (see Figure 5.11, bottom right). Students were then presented with their final representational task along with contextual questions. Question 1: “Draw particle representations to explain a single piece of chocolate at 10°C and another at 20°C.” Ina and Megan constructed diagrams using interactive canvas within the STILE platform and Clara provided a digitally written response (see Figure 5.12).
Ina

<table>
<thead>
<tr>
<th>Piece of chocolate at 10 degrees</th>
<th>Piece of chocolate at 20 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>The particles at ten degrees are moving slower than the particles in the chocolate at a higher temperature (the wavy lines represent movement)</td>
<td>The particles at twenty degrees are moving faster than the particles in the chocolate at a lower temperature</td>
</tr>
</tbody>
</table>

Megan

<table>
<thead>
<tr>
<th>Piece of chocolate at 10 degrees</th>
<th>Piece of chocolate at 20 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-some movement but not nearly as much as 20</td>
<td>lots more movement, because chocolate is warmer the particles are bumping together more</td>
</tr>
</tbody>
</table>

Clara

The piece of chocolate that is 10 degrees will have less kinetic energy and have less movement, but the other chocolate piece which is 20 degrees will have more kinetic energy.

Figure 5.12. The case group’s constructed representations of chocolate at 10°C and 20°C.
Question 1 provided an opportunity for students to respond to the information in the video by re-representing their ideas in different contexts through an EGR-SGR interplay. The question revisited their idea of how particles and their bonds change in a solid where the temperature is changing, requiring them to depict changes in the bonds. The other questions in Activity 5.5 presented hypothetical scenarios in an everyday context. For example, Q2 was: “Explain how an ice cream that is at 4°C can have thermal energy.” Students’ responses are addressed in the Chapter 7.

Module 5 summary

As the first conceptually-focused module showcasing inquiry-based RCA, there were key affordances for this learning platform in supporting students’ uptake of the RCA. In response to their first representational challenge incorporating particle ideas (see Activity 5.2), students generated a variety of imaginative digital and non-digital representations. The range of SGRs indicated students’ natural ability to generate representations and varying levels of representational competence to depict iconic to more abstract representations of these submicroscopic processes (diSessa, 2004; Kozma & Russell, 2005). Students exercised agency when selecting media (e.g., interactive canvases, project book), each providing similar drawing affordances (e.g., shape, colour, text) and quality. Students also expressed their particle ideas using the actional mode (i.e., as a role-play), and then re-represented their ideas in the textual mode (i.e., their written reflection), experiencing a cross-modal translation.

From a socio-semiotic perspective, the quality of learning is related to an ability to move flexibly between representational modes in developing explanations of phenomena (Bezemer & Kress, 2016; Lemke, 2004; Waldrip et
al., 2010). Students’ responses indicated this module challenged them to express and re-represent their ideas in different representational forms, modes, and media, resulting in individual variations. The case group completed all the tasks, addressing most of the required criteria. Though their representations were not formally assessed in STILE or in their project books, this chapter analysis of their conceptual understanding and representational competence showed varying degrees of consistency with the specified canonical ideas. A more detailed analysis is presented in Chapter 7.

The DLE supported the multimodal expression of students’ understanding of the concept of energy transfer across digital and non-digital media, and the potential for a more comprehensive assessment of their ideas. Though there were sometimes similarities in their representations, suggesting a degree of collaboration in this social setting, there were enough variations to indicate students were constructing their own individual learning pathways. This module also featured purpose-made videos designed and produced by one of the chief investigators. The videos integrated macroscopic and submicroscopic processes of the particle model within the context of sustainable housing, providing a rich multimodal resource for students. Similar to the earlier modules, students engaged in EGR-SGR interplay, responding to the content presented in the video through their SGRs.

5.3.2 Module 6: Heat transfer through conduction

Module 6 was the first module where I was able to employ video capture, providing information on the interactions between students and opportunities to conduct a VSRI. Students also undertook their first practical investigation involving dataloggers, a skill integral to their final inquiry task. This module took
place over two consecutive lessons of 60 and 75 minutes respectively. The regular classroom teacher, Sophia, was away for the first lesson. To maintain the representational approach to the unit, Sophia requested I lead the lesson in the presence of another teacher from the school.

*Reviewing students’ prior knowledge through multiple modes*

Through teacher-guided discussion, students reviewed their understanding of climate change and properties of matter, then represented their ideas about particles in a solid, liquid, and gas through gestures or body movement. The use of verbal and actional modes provided insight into students’ conceptions and challenged them to re-represent their ideas across the modes.

The first activity in STILE presented a video introducing conduction. However, there was no internet connectivity, so I created two offline representational activities allowing students to elaborate on their knowledge. I challenged students to represent how heat would travel through a conductor and insulator using role-play. I selected two groups to demonstrate their role-plays and asked them to identify key features (e.g., what represented the particles) as well as key differences in heat transfer for each of the two representations. Their role-plays were videoed.

Ina, Megan, and Clara were in a group of six students. Because clear audio was not possible, I viewed the footage and referred to my field notes to understand how their role-play developed. To model a conductor, students formed a single line, standing close together with their shoulders touching. Ina was on the far left and initiated movement, swaying her shoulders back and forth. One by one, from left to right, each student mimicked the same movement. Then, to model the insulator, they took a step away from each other, creating about 30–50
cm of space between them as they maintained their position in the line. Again, Ina initiated the movement with the students following left to right, moving more slowly than in the previous demonstration.

The role-play focused attention on spatial relations and interactions/movement between discrete particles, prompting a classroom discussion of students’ ideas. Students needed to coordinate the movement of particles with the movement of energy through particle collisions. In response, students stayed in the same place, bumping into each other, suggesting that something (e.g., energy) was moving through the line. The group’s demonstration indicated that they had some challenges with maintaining particle connectedness in the insulator, and as they were so far apart, it was unclear how the energy transferred through collisions. They elaborated on this during their VSRI, which is addressed in the Chapter 7.

*Explicit discussion of representations: Form and function*

The role-play supported a particle model explanation of what was going on macroscopically. Students developed their ideas around the spacing between particles. I clarified the group’s understanding of how particles might be configured in metal and wool and paraphrased the students’ explanation to the class by stating that “when particles were closer together, energy transfer was faster than when particles were further apart”. Because the purpose of this representation was to allow students to explore their understanding, I did not assess their role-play, instead, I focused on clarifying their current understanding.

*From dynamic to static representations: Translation across modes*

After the students demonstrated their role-plays, I asked them to re-represent conduction in conductors and insulators in their project books and
include annotations and titles. The case group constructed the following representations (see Figure 5.13).

**Ina**

**Megan**

**Clara**

Figure 5.13. The case group’s representations of particles in a conductor and an insulator.

The diagram allowed students to re-represent their ideas from an actional to a visual mode, maintaining particle connectedness and motion, and negotiating the modal affordances of each. All three students provided unique representations of their ideas, combining textual and visual modes. Their responses were broadly
consistent with the scientific ideas of particles and their motion. Megan’s was the only diagram of an insulator without particle connectedness.

*Introducing canonical content about conduction (Activity 6.1)*

As a class, students then viewed a four-minute purpose-made video about conduction titled, *Energy Transfer Through Conduction* (see Figure 5.14).

The video provided a particle model explanation of conduction, using the context of housing design. The first frame presented the image of *heat travelling through the iron rod* again (see Module 5 Figure 5.11, and pre- and post-test Q8). The next frame provided an animated submicroscopic particle demonstration of the transfer of kinetic energy through collisions from an area of greater heat to an area of lesser heat, taking place in the iron rod. The animation of Newton’s Cradle represented a macroscopic example of kinetic energy transfer through collisions. In the final frame, the scientific term *conduction* was introduced as a set of collisions of particles in a solid. In addition, everyday examples of conductors and insulators were introduced, including those related to sustainable housing (e.g.,

Figure 5.14. Screenshots of the video *Energy Transfer Through Conduction*. 

The video provided a particle model explanation of conduction, using the context of housing design. The first frame presented the image of *heat travelling through the iron rod* again (see Module 5 Figure 5.11, and pre- and post-test Q8). The next frame provided an animated submicroscopic particle demonstration of the transfer of kinetic energy through collisions from an area of greater heat to an area of lesser heat, taking place in the iron rod. The animation of Newton’s Cradle represented a macroscopic example of kinetic energy transfer through collisions. In the final frame, the scientific term *conduction* was introduced as a set of collisions of particles in a solid. In addition, everyday examples of conductors and insulators were introduced, including those related to sustainable housing (e.g.,
insulation batts, double-glazed windows). This purpose-made video related the macroscopic and submicroscopic processes of conduction with relevant examples and was a unique representational resource for this unit. Following the video, students addressed questions regarding particle collisions in different materials. The second video in this unit focused on people’s informal understanding of conduction based on everyday contexts (e.g., the difference in temperature between a cake and the tin it was baked in). The follow-up questions had students reflect on their learning and are addressed in Chapter 7.

*Summative assessment: Applying ideas in other contexts (Activity 6.1)*

The final three questions of the unit were multiple choice, based on key ideas presented through various scenarios, as a summative assessment of students’ learning (see Appendix C). The questions were also aligned with the unit pre-test so provided insight into students’ conceptual development. The average score of the class was 50%, but each of the three students in the case group had a score of 33%, though their responses differed somewhat. A more detailed analysis of the students’ responses is addressed in Chapter 7.

The online platform provided a unique affordance for this summative task: students’ responses, correct or otherwise, generated an *automated instant feedback* response, providing nuanced feedback for each response. For example, Q4 focused on the everyday context of cooking and presented challenges for all students in the class, with 75% of all students answering incorrectly, including the case group. The question stated: “A cook uses an iron frying pan to cook a meal. After cooking, he places the hot frying pan on the counter. After a while, the frying pan, the counter, and the air in the room will be at the same temperature. Why?” All three students chose the same answer: “Because thermal energy will
be transferred from the frying pan to the counter and from the frying pan to the air, and coldness will be transferred from the counter to the frying pan and from the air to the frying pan.” The automated feedback explained: “You are partially correct. Thermal energy will be transferred from the frying pan to the counter and from the frying pan to the air. However, there is no such thing as coldness and so will not transfer from the counter to the frying pan and from the air to the frying pan.” The feedback was specific to students’ responses and focused directly on the alternative conception that coldness transferred, providing the canonical explanation. This automated feedback feature was a departure from most multiple choice tests which indicate a right or wrong answer with no further feedback, and therefore more consistent with ideas of learning through formative assessment.

Conduction part 2: The heating investigation

The following day, students continued with the conduction module led by their regular teacher, Sophia. To review the previous lesson for the teacher, students demonstrated their role-play comparing how heat transfers in conductors and insulators and briefly summarised the differences. While I was interviewing the case group, the other students completed their diagrams in their project books along with Module 6 questions. After the interview, all students were oriented to the dataloggers before they undertook their investigation. Students shared the results of their investigations through a whole-class discussion. I used video-capture for this lesson, but as I was focused on other groups, I was not able to provide video-based evidence for the case group.

Explicit discussion of representations

As students were demonstrating their role-play in front the class, one student, Angela, explained what was happening:
**Angela:** So our conductor is closer together and vibrating [students’ standing in a single line shoulder to shoulder and swaying]. And then our insulator is more spread out [students take a step apart from one another and continue swaying] and faster.

**Sophia:** What differences would there be, in what you are showing and representing, in terms of conducting heat?

**Angela:** Well, in the conductor there’s…more denser and it’s easier for heat to travel through.

**Sophia:** OK, any other comments?

**Students:** [no response]

The dialogic interactions between the teacher and students indicated a potentially rich discussion about the purpose and evaluation of representations. However, there was no discussion around what their actions were representing, what concepts were highlighted, what other representations might be used, and how to refine their role-play, which contributes to conceptual and representational development.

*The first practical investigation: Conduction (Activity 6.2)*

The Heating Investigation was designed to orient students to data logging equipment, which played an important role in their final Sustainable House Inquiry task later in the unit. Prior to starting the investigation, I demonstrated how to use the dataloggers, then students reviewed their understanding by watching a short instructional video from their laptops in their groups. For this investigation, students recorded temperatures from two temperature probes: one of which was covered with students’ choice of material (e.g., aluminum foil, bubble wrap, cellophane, coloured paper) as a single heat source (i.e., heat lamp)
shone on them. After the investigation, students responded to the three questions on STILE, which was related to their prediction and results. Both Ina and Megan predicted the foil-covered probe would heat up faster than the uncovered one, and Megan indicated that the foil would conduct the heat. They uploaded the same photo of the temperature graph generated from their datalogger (see Figure 5.15).

![Image of LabQuest 2 datalogger](image)

Figure 5.15. The case group’s temperature graph for the Heating Investigation.

The datalogger generated real-time temperature data tables and a graphs on two separate screens. This was the first example of two-way mapping, where the observable phenomena (i.e., temperature rising) was linked directly to its representation (i.e., the graph), providing a direct connection between the referent and the representation. There was a learning curve in using this technology, which caused some concern for both the teacher and the students. As it turned out, most of the temperature probes in the classroom were not working so students had to generate individual graphs for each trial instead of doing both concurrently.

The activity provided the overall aim and method, while allowing for student choice on the material covering the probe. As an instructional resource,
STILE had the capacity to support a number of features of the learning experience. Firstly, it had an embedded instructional video on how to use the datalogger, allowing students to review as needed as they were orienting to the new technology. STILE also enabled students to upload their digitally-generated graph, incorporating materials outside the platform. Finally, the scaffolding of the questions in STILE was similar to a formal laboratory report, eliciting students’ predictions prior to the experiment, and having them present and interpret the data. However, the design of the questions did not elicit students’ causal explanation of their results or provide additional representational activities to explain any underlying mechanisms in conduction. The follow up discussion led by the teacher focused on the results of the investigation, along with the technical issues of the equipment, but again did not focus on causal explanations that might have elicited students’ consideration of the underpinning representational systems.

Module 6 summary

This was the first module featuring video-capture and a practical investigation. It presented insights about students’ interactions with the representational resources provided, through the perspective of RCA. Similar to Module 5, the students expressed their ideas through different modal affordances (i.e., role-play, discussion, diagrams). However, their responses to the embedded assessments (i.e., Activity 6.1) suggested alternative conceptions and limited uptake of conceptual ideas.

Though the video record provided access to conversations throughout this module, the nature of the discussions around representations were limited. RCA-focused discussions involve students explaining, comparing, and evaluating
representations as a whole-class activity of meaning making and consensus building of knowledge. This level of interaction supports students’ conceptual and representational understanding through active participation in epistemic knowledge-building processes (Prain & Tytler, 2013). Though students were generating multiple and multimodal representations, they were not engaging with this discursive practice; and, similar to Module 5, were not receiving feedback in STILE or their project books. As a result, students were not receiving formative assessment of their conceptual and representational development.

Similar to the video in Module 5, the purpose-made videos provided rich multimodal resources for the students. The conduction video integrated macroscopic and submicroscopic processes of the particle model in the context of conduction. This module also featured students’ first practical investigation in the unit, which was supported by a video-based instructional resource for the datalogger, image-loading capability in STILE, and questions to scaffold the reporting. However, there were no structured opportunities for students to map their observations of the phenomena investigated with an explanatory particle-level representation of conduction (e.g., why the foil covered probe heated faster), missing a critical link in supporting students’ conceptual development in this practical investigation. In addition, there were no representational challenges.

5.3.3 Module 7: Heat transfer through convection

Module 7 featured a stronger teacher orchestration of activities, more teacher-class dialogue than any other videoed lessons, along with the addition of a teacher-led demonstration outside the STILE curriculum. It also featured a post-investigation mapping activity. The one-hour lesson began with the teacher-led introduction to convection. Students then viewed the online video and responded
to STILE-based questions. They watched the teacher do a short demonstration on convection and discussed how the key concepts of convection applied to the STILE questions. In groups, students did the teabag rocket activity (i.e., involving a teabag burning and lifting through convection currents in the air) and related their experience through online questions and an SGR. The video-capture in this lesson involved other groups, so I was not able to provide video-based evidence for the case group.

**Reviewing students’ prior knowledge through their everyday experience**

To introduce this module, Sophia engaged students in a dialogue relating convection to their everyday experience of home heating and cooling systems. She followed the initiate-response-evaluation strategy (Scott & Mortimer, 2005) to sequence her dialogue about how heat transfers in fluids through convection, relating the process to home ducted heating systems. This sequence took place outside the STILE module as a teacher-led introduction that provided an everyday experience to relate to the topic. Throughout the sequence, Sophia only provided prompts and refrained from providing any scientifically authorised information. The students participated by raising their hands in response to her questions.

**From EGR to SGR: Students re-represent their understanding (Activity 7.1)**

After the whole-class interaction, students viewed the first video in module, titled *Energy Transfer by Convection*. Similar to the videos in Modules 5 and 6, this purpose-made video linked macroscopic and submicroscopic processes, providing students with examples of energy transfer in a liquid (e.g., thermal energy transfers from the hot plate through the saucepan) and relating this still image to animated ones that incorporated particle ideas and the use of arrows to depict convection currents (see Figure 5.16).
Figure 5.16. Screenshots of the video *Energy Transfer by Convection*.

While showing the video, Sophia paused and highlighted specific points, engaging students in dialogue. For example, part way through the video, when the narrator was describing the representation with the saucepan and arrows, Sophia paused the video and addressed the students:

*Sophia:* What are you noticing? What’s happening? Here’s our flame, what’s happening?

*Student:* The warmth is rising up and the cool, the cold is coming down.

*Sophia:* Perfect! So that’s creating a current.

Sophia continued showing the video, which explained convection currents at a particle level and related them to global processes (e.g., liquid rock underneath the Earth’s surface, weather patterns), along with everyday examples in the house (e.g., heating and cooling) (see Figure 5.17). The video concluded by providing five key points about convection, which the students copied verbatim into their project books (see Figure 5.18).
Figure 5.17. Final screenshots of the video *Energy Transfer by Convection*.

After showing the video, Sophia asked students to either directly record the key points in their projects books or to draw a representation showing the convection cycle. She encouraged them to construct representations and provided the following prompts:

I challenge some of you, if you are feeling confident, to draw some kind of heat source, and then I want you to see if you can represent it diagrammatically, if you are confident, potentially using arrows and maybe explaining what is happening here. So…the heat source, what particles are rising to the top? Why are they doing that? Are they more dense? Are they less dense? What’s happening to the cooler ones?

The case group responded by recording the five key points provided in the video and representing their ideas about heat sources (see Figure 5.18).
Figure 5.18. The case group’s list of the key points and their representations about convection.

All three students recorded the key points on convection exactly as they appeared in the final slide of the video. Their diagrams resembled the digital representation featured in the video (e.g., position of radiator and window, direction and color of arrows, annotations) and followed the same red-blue arrow convention correctly indicating the hot air rising and the cool air sinking.
An impromptu teacher-led demonstration

After the video, Sophia incorporated an impromptu demonstration about convection based on her learning that students had not experienced this demonstration before. She performed the potassium permanganate demonstration, which showed how a convection current flows in liquids, enacting the boiling water animation in the video. Throughout her demonstration, she asked a series of questions to the whole class: “We are going to place a couple of drops in the water, then heat it up. What do you think will happen? What will we see?” The dialogue continued:

*Sophia:* After 5 minutes, what colour will the water be?
*Students:* Purple?
*Sophia:* Evenly?
*Students:* No?!
*Sophia:* Evenly?!
*Students:* No?
*Sophia:* So what should we see, because this is a fluid, similar to the diagram we drew, what should we see happen?
*Students:* It will rise?
*Sophia:* Right! And because of the colour, we should be able to clearly see that. So you should actually see the convection current. So what’s moving upward?
*Students:* Heat! Currents!
*Sophia:* Are they more dense or less dense?
*Students:* Less!
*Sophia:* Yeah. And as they start to cool from the top, are they becoming
more dense or less dense?

**Students:** More!

**Sophia:** As they are starting to cool...did you say more?

**Students:** Yes!

**Sophia:** And so where are they going?

**Students:** Down!

**Sophia:** Yeah, and that’s why we have this current. Can you see that, kind of current happening? [After a few minutes] What’s happened to the colour? Is it even?

**Students:** Yes!

The dialogue focused students’ attention on the movement of convection currents, and the eventual result where the colours were evenly distributed. In addition to the IRE sequence, this was another example of Sophia integrating activities outside the STILE curriculum to adapt the lesson.

*Formative assessment: Applying ideas in other contexts*

Students then proceeded to respond to the questions in STILE, applying their ideas to everyday contexts. The first question had students to explain how a breeze or a fan cools the body. This question was challenging for the student and required prompting by the teacher (see Chapter 7). The other two questions required students to add arrows to diagrams to depict the convection current (see Figure 5.19), for example Q2 stated: “In the picture below, there is a diagram of a lit candle and a magnified image of the candle flame. Draw on the left-hand diagram arrows to show how heat from the candle flame will start a convection current. On the magnified image of a flame, represent how energy from the flame transfers to energy of the air using particle ideas” (see Figure 5.19).
Figure 5.19. The case group’s representations for convection currents around a candle.

Question 2 provided an initial image from which students added their ideas. This focused their attention on convection currents. Students’ responses needed to depict a convection current as the heat energy transfers from the wick to the air, where the hotter or less dense air around the flame rises and is replaced by the cooler or more dense air from below. All three students showed an understanding of the broad movement of the convection currents, though Ina and Megan copied their previous pattern of currents. The particle explanation around the flame was particularly challenging. Both responses depicted ideas of motion and decreasing particle density. The final question focused on convection currents in a hot water system.

Question 3 also provided an initial image from which students added their ideas: “The diagram below is a cross-section of a hot water system you might have in your home. It is a tank full of water with a heating element and two
openings. When the heating element is turned on, hot water flows out of the system and cold water flows in. Using your understanding of convection, indicate with RED coloured arrows the direction the hot water takes and indicate with BLUE coloured arrows the direction cold water takes. Indicate which should be the hot water outlet and why” (see Figure 5.20).

In response, all three students followed the red-blue convention prescribed by the question. Their responses needed to show the cold water intake on the bottom left and hot water flowing out from the top right, where the hot water outlet would be. Though the case group correctly depicted the flow of the current, none of them correctly addressed all aspects of the question.

*Hands-on activity: Teabag rocket (Activity 7.2)*

Students constructed a teabag rocket to demonstrate convection. To introduce the activity, the teacher showed a one-minute instructional internet-based video on STILE summarising the investigation. As the video was playing, Sophia asked students to think about what was going on inside the teabag when it was being projected upwards. Sophia provided guiding questions: “You need to
think about is there a fluid inside that bag? What’s happening with the convection current and why is it going up?”

**Mapping observations with representations**

After the investigation, some of the students were not able to connect to the internet to complete the questions in STILE so Sophia provided the following prompts to assist students in writing in their project books as an alternative:

Why do you think ducted heating is often placed on the floor, where hot air is coming out, and evaporative cooling vents are placed on the ceiling? Otherwise, think about the teabag rocket. What fluid is inside the teabag tube? What is heating going to do to that fluid? How can you draw that convection current? And why then, is that rocket rising in the air?

From their hands-on experience, students were challenged to construct representations of the convection current in the teabag. Ina and Megan uploaded their representation (see Figure 5.21). Students then responded to Q1: “Use your understanding of energy transfer to explain why the ash of the teabag rises up into the air? You can use text and/or drawings to provide an answer in your journal. Take an image of your answer and upload it here.”

<table>
<thead>
<tr>
<th>Ina</th>
<th>Megan</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Ina's representation" /></td>
<td><img src="image2.png" alt="Megan's representation" /></td>
</tr>
</tbody>
</table>

Figure 5.21. Teabag rocket representations by Ina and Megan.

The two-way mapping of the observed phenomenon to representation provided a stronger conceptual focus to the practical investigation. Ina and Megan combined visual and textual modes to explain the convection currents in the
teabag rocket. The diagrams allowed them to express both a spatial and textual explanation of where the current is moving in relation to the heat and provided an important yet often neglected conceptual focus in practical investigations. Students applied the same red-blue up-down arrow conventions they used throughout the unit, in both water and air, suggesting a strong uptake of the ideas presented in the convection video.

**Module 7 summary**

Similar to Module 6, the teacher included activities outside the STILE module to engage students in face-to-face dialogue and activities. Sophia oriented whole-class discussions around real-life examples as a way to support the relevance of the topic. She presented a live demonstration to support students understanding of convection currents, though there was no opportunity for two-way mapping. These additions demonstrated that the teacher was not following the STILE curriculum in a step-by-step manner, but instead adapting the learning sequence. Similar to the purpose-made video in Module 6, the convection video provided a rich representational resource, linking macroscopic and submicroscopic representations across everyday contexts. In contrast to the heating investigation in Module 6 (see Activity 6.2), students were provided with a post-investigation activity where they constructed representations to explain the convection currents in the tea bag rocket, enabling them to link the phenomena to their SGR for a stronger conceptual focus. However, students’ understanding of convection currents was also strongly influenced by the initial video, as they repeated the pattern of circulation throughout their SGRs with limited adaptation across contexts. Similar to Module 6, there were no representational challenges.
Though there was more evidence of teacher-class dialogue, these were not oriented around SGRs.

5.3.4 Module 8: Heat transfer through radiation

As the final in the series of four conceptual modules, the single 75-minute module focused on energy transfer through radiation using two new instructional resources. The first was a video using a Physics Education Technology (PhET) animation, which had digital EGR-SGR capabilities providing an interactive experience for scientific concepts (see https://phet.colorado.edu). The second innovation was a representational challenge involving a digital media presentation. Sophia introduced the topic through the STILE curriculum, asking a student to read the Key ideas provided in the module as it was projected on the screen and to generate questions about them (see Table 3.1). The class then viewed videos on Infrared Radiation and Electromagnetic Spectrum (ES) and responded to the question in STILE. Finally, Sophia introduced the summative task for the module, which involved students creating a digital media representation synthesising ideas related to radiation and the electromagnetic spectrum. Due to time constraints, only Activities 8.1–8.3 were addressed, missing 8.4 and 8.5 (i.e., radiation, the atmosphere, greenhouse effect).

Assessing students’ prior knowledge

After a student read the Key ideas aloud, Sophia provided students with a small handout of these ideas and directed students to affix it into their project books. From these ideas, students generated their own questions about radiation. The case group recorded their questions in their project books. Figure 5.22 shows Ina’s responses.
The introductory activity assessed students’ prior knowledge through the questions they generated. From the Key ideas, Ina generated the following questions: “What is an entity? What is the difference between types of radiation? What does radiation do? What is the electromagnetic spectrum used for?” Megan wrote: “What do all the types of radiation mean? What does entity mean? What does the electromagnetic spectrum look like?” Clara wrote: “What is entity? What is gamma radiation? What are the differences with the different types of electromagnetic spectrum?” Sophia asked students to share their questions, without providing any answers, and then showed the first video in STILE.

*From EGR to SGR: Student re-representing their understanding about waves (Activity 8.1)*

The purpose-made *Electromagnetic Radiation* video featured text, images, animations, and a PhET animation, integrating a variety of expert-generated static and dynamic macroscopic and submicroscopic representations (see Figure 5.23).
Sophia paused the video at the diagram of the electromagnetic spectrum that was featured in the module, provided a brief definition of it, and highlighted key points:

It is a spectrum of electromagnetic radiation. Somewhere in there, you will see visible light. Somewhere beside that you will see ultraviolet radiation, you’ll see x-rays and gamma rays – over here, with some of the lowest frequencies. Do you know what your mobile phones use? Pretty sure they are microwaves. And so we are going up in terms of frequency here, so if you go up on STILE, the image will be much clearer.

The PhET animation demonstrated how radio waves were transmitted from an aerial transmitter (i.e., how vibrating an electron in a wire creates
electromagnetic radiation, a form of energy that travels like a wave). The animation explained radiation as vibrating electric particles and electrons, and demonstrated that the frequency of the vibration can result in a more energetic radiation signal. The two PhET images in Figure 5.23 (see middle row) showed the animated differences in amplitudes and frequencies in waves. Using the PhET animation, Sophia demonstrated that the quicker the electron moves, the greater the frequency (i.e., the number of waves). She then read aloud Q1, explained the key terms, and encouraged students to draw directly on the interactive canvas or upload diagrams from their project book.

Question 1 (note terms are bolded as they appeared in the question):

“Electromagnetic Radiation is often described as having a specific frequency. Radiation sent in the signals between the radio station and your radio has a low frequency (the signal is called a radiowave) whereas the radiation in the signal sent between mobile phones (the signal is called a microwave) has a higher frequency. In the space below, represent using a wave representation the difference between a radiowave and a microwave. Also, in the space below represent a weak microwave signal compared to a strong microwave signal like you often find when you are using your mobile phone from different locations. Label your representations”. The case group generated the following representations (see Figure 5.24).
Figure 5.24. The case group’s representations comparing waves.

The response required representations to depict strong and weak waves with different amplitudes but the same wavelength. The case groups’ responses were varied, addressing some of the criteria with inconsistencies: Ina’s frequencies differed in wavelength, Megan did not clearly distinguish the difference of a radiowave, and Clara’s diagram was strongly influenced by the PhET animation.
From EGR to SGR: Student re-representing their understanding about the electromagnetic spectrum (Activity 8.2)

After a brief introduction, Sophia showed the second video from the internet titled, What is the Electromagnetic Spectrum? This internet-based video provided a two-minute narrated explanation using images and animations, comparing the wavelength and sources. Students were meant to complete the interactive fill-in-the-blank table in STILE as an EGR-SGR interplay. However, a design flaw presented it as a static table, so Sophia reviewed their answers through a whole-class discussion, elaborating on examples provided in the table and providing additional examples. Similar to the first activity, this one also contained a large amount of canonical information in addition to a very structured question. Sophia adapted to the technical issue (i.e., lack of interactivity in the table), providing non-digital engagement with the content. The lack of interactivity likely impacted students’ learning and is addressed later in this section.

Summative assessment: Applying ideas in other contexts (Activity 8.3)

The final activity involved a group-based representational challenge involving a digital media presentation. Students used the internet to investigate one type of electromagnetic radiation of their choice and generate a presentation, using media of their choice. The questions in STILE were used as prompts by the students: “Where is the radiation type located on the electromagnetic spectrum? What are the natural sources of the radiation? What are some of the artificial sources of the radiation? What are at least two beneficial uses of the radiation by humans? Are there any dangers of the radiation for humans? List a feature of the radiation that is not common to other types of radiation?” Ina worked with Megan
to create slides (see Figure 5.25), while Clara worked with another student outside this case study to create a mind map (see Figure 5.26).

Figure 5.25. Activity 8.3 Examples of the first two slides for Ina’s and Megan’s presentation.

Ina and Megan created an eight-slide presentation using Google Slides, organised by the prompts, and using only two still images from the internet (see Figure 5.25). During a VSRI, Megan and Ina elaborated on their experience constructing their presentation.

*Reflection on the PowerPoint presentation*

Google Slides enabled students to work collaboratively on the project without having to be in the same place, expanding the distributed learning environment. Ina indicated that they worked on it together in class, and a bit on their own over the weekend. Later in the interview, Ina explained why they used the slides instead of their project books: “Well I guess it was ‘cause we could both work on it at the same time, and that’s a plus. And also it just looks nicer and it presents nicer than if you just wrote it down, for something to submit like, it feels bit nice to have it all done. And it’s easy to set up, too. Just with a slide for each question.” Clara and her partner, Anna, chose to use the Mind map application on STILE to construct their presentation about gamma radiation (see Figure 5.26).
Clara and Anna also used the same prompts provided by the questions to guide their response. They indicated it provided an easy and visual way to address the questions. The online learning platform accommodated digital choices for the students’ unique learning pathways. Although both groups demonstrated proficiency in the digital technologies, their responses were primarily textual, integrating the prompts provided in the question, and required minimal coordination of representations. In addition, neither integrated waves models into their explanations.

Module 8 summary

Compared to the other modules, the radiation module foregrounded more canonical and abstracted content, with a different balance of EGRs and SGRs, and no hands-on or problem-solving activities. The purpose-made video featured several sophisticated representational-rich resources (e.g., PhET animations). The
first SGR-related question (Q1) presented several new scientific terms at once. Though it was the only activity where students generated representations (i.e., diagrams), the transition to the wave model of energy transfer was a striking departure from the particle model, with no material connection. Activity 8.2 was experienced as a teacher-led presentation due to technical issues with the questions in STILE. Though Activity 8.3 was a representational challenge, it involved limited coordination of representations for meaning-making processes and overemphasised textual modes. Activities 8.4 and 8.5 (i.e., radiation, the atmosphere, greenhouse effect) were not addressed due to time constraints, which likely impacted students’ post-test results and overall learning. These four modules, Thermal Energy, Conduction, Convection, and Radiation were designed to provide the conceptual foundation to support students’ summative Sustainable Housing inquiry task. The next chapter focuses on how Ina, Megan, and Clara applied their skills and conceptual knowledge during this summative task.

5.4 Chapter Summary

Where Chapter 4 suggested a flexible multimedia and multimodal learning environment supporting variation in learning pathways, Chapter 5 presented the variety of students’ multimodal responses across the media resulting in their unique learning pathways. The overall findings in this chapter identify key generative features of the learning environment and patterns in the design and delivery the learning sequences that have implications for students’ learning.

5.4.1 Generative features the learning environment in supporting RCA

The notion of generative features emerges from the socio-semiotic and epistemic theoretical perspectives which underpin RCA. The term refers to dynamic processes to construct meaning and plans of action (Wittrock, 1992). For
this research setting, generative features in the unit design and delivery support meaning-making processes. The most generative feature of this DLE was that the cloud-based learning platform functioned as a flexible learning tool. As an authoring tool, the teacher-research team were able to modify the online learning platform for their own pedagogical purposes, integrating their interpretation of the prescribed curriculum and delivering it through an active knowledge-construction pedagogy. The learning platform also accommodated individual and social learning opportunities and allowed students to move across face-to-face and online environments as a cohesive learning experience. Students participated in individual tasks throughout the unit (e.g., surveys, generating representations, answering questions in STILE), often choosing the tools and media to construct their own learning pathways (see Chapter 7). Students also worked in groups, engaging in whole-class (e.g., diagnostic discussions, demonstrations) and group-based tasks (e.g., dynamic role-plays, practical investigations, digital media presentations), learning through social interactions.

The online learning platform expanded access to multiple media and multimodal representational resources for instructional design (e.g., purpose-made videos, dataloggers) and knowledge exploration and construction (e.g., surveys, role-plays, interactive canvas, practical investigations). The interactive digital canvas supported a variety of SGRs equivalent in quality to hand-drawn SGRs. Assessment applications such as the Live Poll and Automated Instant Feedback provided more visual and interactive feedback than just simple right or wrong responses, supporting social and constructivist learning processes. Students also accessed the Class Discussion (CD) application which enabled informal online messenger-like communication. Though it was not part of the intentional
design of the unit (i.e., it was used for off-task communications), CD enabled informal online messenger-like communication. Students’ concurrent use of digital and non-digital media and the resulting variation in their responses demonstrated the degree of agency they experienced in this inquiry-based learning environment.

The online learning platform also accommodated hands-on activities that took place as group-based face-to-face tasks that were scaffolded online. The heating investigation involved the use of sophisticated equipment (i.e., datalogger), which required more elaborate training provided through the combination of a live explanation and an instructional video. STILE also enabled students to upload images of the datalogger graph(s) onto the platform to construct an integrated media report. Though the platform scaffolded questions for a report, these questions lacked a specific conceptual and representational focus, missing an opportunity for students to use the representations to develop causal explanations. The teabag rocket activity also included an instructional video, which prepared the students for a more successful experience with this one-time only event. In contrast to the practical investigation, this activity included an offline follow-up activity where students represented the convection currents in the teabag, providing an important conceptual focus for this activity.

In the Questionnaire (see Appendix A), students were asked about how their experiences with the platform (see Q4). They indicated the key benefits oriented around their ability to access information and resources from school and home, along with how STILE presented and organised the unit. Students also indicated challenges with accessing the platform due to technical issues. The affordances
and implications of the online learning platform is addressed in the Discussion Chapter.

As the second key generative feature, the videos presented specific affordances as representational resources. Videos were embedded at specific points within the learning sequence followed by activities to support students’ uptake of the information as an EGR-SGR interplay. The videos could also be delivered as a whole-class or group-based activity. In the former, the teacher paused the video and highlighted key points to focus students’ attention; in the latter, students had agency to pause and replay as needed, fostering a deeper understanding of the material (Berk, 2009).

Videos were featured throughout six of the eight modules and were either internet-sourced or purpose-made. The use of internet-sourced videos provided students with canonical and contextual scientific information about climate change and sustainable housing, public perspectives on convection, and a preview of a practical investigation. The purpose-made videos provided instructions on how to use the datalogger, and also integrated macroscopic and submicroscopic processes of particle and wave models within the context of sustainable housing, providing a rich multimodal resource for students. Though the Questionnaire did not specify videos, students indicated the videos were helpful learning resources (see Q4). The design of purpose-made videos as well as the timing of these canonical resources in the learning sequence are addressed in the Discussion Chapter.

Although STILE enabled the lesson sequencing, the instruction required the teacher’s ongoing orchestration and adaption of activities to support students’ learning. She encouraged them to express their ideas through representations (see
Activities 7.1, 8.1), directed them toward using certain media, and assisted them with available tools (e.g., interactive canvas, dataloggers, Google Docs). She also provided experiences outside the STILE curriculum (e.g., convection demonstration), and when there were connectivity issues, provided offline representational activities (see Module 6, Activity 7.2). Although the potential for discussions around SGRs were unmet, the teacher had an important role in enacting the RCA experience.

5.4.2 The learning sequences and the nature of SGRs

The unit as intended was designed to follow an inquiry-based RCA, where students generate, compare, coordinate, and refine multimodal representations as they explore phenomena. This guided process involves teacher-facilitated negotiation around SGRs, to engage students in the active knowledge production process, provide ongoing assessment of their learning, and move them towards a more scientific understanding. Although much of the learning sequence was embedded in the cloud-based platform, the teacher orchestrated the interactions and made some adaptations. Overall, the unit as experienced enacted some aspects of RCA, including inquiry-based processes, and sequenced activities to support conceptual and representational development and ongoing assessment. The unit design reflected the key features of the socio-semiotic RCA pedagogy: a strong conceptual focus situated within a relevant context (i.e., climate change and sustainable housing); a guided inquiry approach to activities and questions that allowed student choice, flexibility, and collaboration; a variety of representational resources by which students could construct meaning; and, ongoing formative and summative assessment.
The learning sequence was embedded in the cloud-based platform, consisting of both face-to-face and online activities that were consistent with the socio-semiotic RCA perspective. Across the modules, there were many opportunities for students to engage in EGR-SGR interplay where students represented their ideas in response to canonical information (e.g., videos). To a lesser degree, students also experienced representational challenges (i.e., Modules 5, 8), cross-modal translations (e.g., the role-play to drawing task in Module 6), and two-way mapping (e.g., the post-activity drawing in Module 7).

In response, students generated a variety of multimodal representations (e.g., mind maps, drawings, role-plays), with many digitally constructed. The interactive canvas in STILE supported similar drawing affordances to the project book, allowing students to generate annotated diagrams and express ideas using shape and colour. Despite students’ ability to generate equivalent quality SGRs in the interactive canvas and their high use of this digital option, their responses in the Questionnaire indicated they had challenges (see Q4 and Q6). Most of the students’ preferred using their project book and identified specific challenges in constructing digital SGRS; this was attributed to the capabilities of their laptop and within Paint application. Students stated that it was easier to draw in their books. One student commented: “Using paint was challenging because it was hard to get the drawings accurate and it was challenging to share the drawings”. Many students cited specific challenges with drawing in the Paint application, including difficulties with the paintbrush within the application, the laptop pen, and using the touchscreen directly with fingers. Another student explained why she used both media, supporting the importance of providing students choice: “I also used the project book to draw some of the diagrams that were hard to draw
students’ perceptions imply the need for more support in using this application. These issues are addressed in the Discussion Chapter.

The actional mode of the role-play presented visuo-spatial affordances that elicited information about students’ persistent alternative beliefs. In Module 5, students learned how to incorporate particle ideas to explain concepts about energy transfer. By the end of these conceptual modules students were more consistently coordinating representations with both macroscopic and submicroscopic processes to explain phenomena (e.g., motion in solids, energy transfer through conduction, convection currents in the teabag rocket).

Assessment of students’ knowledge took place throughout the unit, providing them with opportunities to express and refine their knowledge across the modes. Diagnostic assessments were embedded in the earlier modules (i.e., Modules 1, 4, 5) and incorporated digital media (e.g., surveys, word clouds, mind maps). In addition, the teacher integrated non-digital activities outside the planned sequence (e.g., role-plays, whole-class discussions). Summative assessment was embedded at the end of the modules as closed-ended multiple choice questions (e.g., Modules 5, 6).

Though these positive features reflected a strong commitment to a representation-rich learning environment, some key aspects of RCA were less evident in the design and implementation, which likely limited opportunities for higher-level conceptual learning. Though most students completed the embedded assessments and received automated feedback in STILE, none were formally assessed or discussed, missing opportunities to address specific misconceptions and adapt activities accordingly. Though I did not have a complete record of the
dialogue across the modules, the nature of the teacher-led dialogue in Modules 6 to 8 also suggested limited discussions around representations. The analysis in Chapter 4 indicated that a large amount of dialogical interactions occurred, suggesting opportunities for comparative and evaluative discussions were possible. However, apart from the teacher-led dialogue around the introduction to the modules, and some prompting around the tasks, there was no evidence of extended discussions around the purpose of representations, their form and function, partial nature, and adequacy. Nor was there evidence of ongoing dialogical evaluation of SGRs towards a more scientific understanding. The likely impact of the lack of these formative processes on students’ conceptual and representational development is addressed in the Discussion Chapter.

The DLE provided flexible and expanded access to multiple media and multiple representational resources to support an active inquiry-based socio-semiotic approach. However, the omission of formal ongoing feedback through discussions and assessment of students’ responses suggested challenges in enacting a demanding and interactive pedagogy and requires the need for more built-in processes to support these interactions. As an authoring tool, the STILE platform supported an interactive pedagogy that allowed the flexible sequencing of face-to-face and online instructional and representational resources. It supported individual and group activities and the development of digital SGRs using the interactive canvas application. Thus, the STILE-based unit went beyond a content repository based on transmissive delivery, memorisation, or a self-tutored curriculum. It supported the teacher’s orchestration of individual and social multimodal learning interactions following the epistemic processes of science. It facilitated students to actively engage in communal knowledge-
building activities and develop individual learning pathways. The potential for
digital delivery of RCA along with the design and timing of the canonical
resources are explored further in the Discussion Chapter. The next chapter
introduces the Sustainable Housing Inquiry, focusing on students’ experiences of
the summative task for this unit.
Chapter 6. Students’ Experience of the Sustainable House Inquiry

Over the final three lessons of the unit, students engaged in a task that required them to apply their understanding of concepts related to energy transfer. This summative activity was designed as a group-based guided-inquiry around the context of passive designs for sustainable housing and was the only formally assessed task for the unit.

This chapter presents an overview and key design features of the summative task and students’ engagement in the scientific investigation. It addresses RQ2: How did the summative inquiry task support epistemic processes representative of scientific practice? Epistemic processes are foundational to knowledge discovery and production in science. These processes involve the development, negotiation, verification, acceptance, and sharing of ideas through consensus across multimodal representational resources (Tytler & Prain, 2012). They are enacted through the exploration of genuine problems and joint construction of representations to justify claims (Tytler & Prain, 2013b). Discourse is central to the collaborative reasoning which underpins these epistemic processes (Driver et al., 1994; Mercer, 2004; Mercer et al., 2004a). The task was designed to induct students into scientific inquiry by engaging them in collaborative knowledge building and communication practices through authentic inquiry questions. With scaffolding and directed choices, the students were asked to address relevant questions through the ongoing generation and refinement of their ideas, reflective of scientific inquiry (Prain & Tyler, 2012; Tytler et al., 2013b).

I argue that the task design supported students’ engagement through collaborative reasoning processes, resulting in an initially chaotic and eventually
more refined conceptual explanation of their results generated across a variety of representations. The video capture produced a record of students’ dialogue, their reflections through VSRI, and their interactions around representational resources. Most of the students’ VSRI responses are featured in a separate grey box to distinguish them from the regular classroom processes. I used three frameworks to support my analysis: a DCog framework to understand the broader interactions within each of the key stages around this task; a dialogical framework to analyse the nature of students’ dialogue around this joint-problem solving task; and an RCA reasoning framework to account for informal and formal reasoning processes. Similar to the previous modules, the analysis was informed by socio-cultural semiotic perspectives that underpin RCA to understand how students were making meaning together through multimodal representations. Students’ experiences are reported through the case group’s perspective on how they designed, conducted, and reported on their inquiry-based investigation. The discussion is organised according to the three stages of the task. To begin, I present the frameworks and the design of the task.

6.1 Applying a DCog Framework to Understand Learning During a Complex Task

I applied a DCog framework to understand how the case group’s conceptual understanding progressed in relation to the representational resources provided by this DLE. The unit of analysis included the interactions of students with representational resources and their emergent explanatory accounts, encompassing a cognitive system of people and tools performing a routine but complex and collaborative task (Halverson & Clifford, 2006; Hutchins, 1995; Zhang & Patel, 2006). I organised the analysis into three stages: Planning the
*Investigation, The Experiment,* and *The Report,* to identify potentially distinct interactions and outcomes within each of the subtasks. Focusing on the interactions during the subtasks and how they supported the larger task enabled me to understand the contextual conditions for an effective cognitive system (Halverson & Clifford, 2006). DCog analysis offered insight into students’ learning, structuring information about the nature of social interactions, the cultural practices, and the mediating tools needed to support a task in a complex learning environment (Halverson & Clifford, 2006; Tenenberg & Knobelsdorff, 2014).

### 6.1.1 Design of the task

The summative assessment was initially developed by a teacher in the school as a way for students to apply their learning to the design of a sustainable house. It was refined by all the science teachers, including Sophia, over two years based on students’ responses, with a stronger integration of the RCA through guided-inquiry, more student choice of media for presenting their report, and improved support for group collaboration. The knowledge for this task encompassed the entire planned content of the unit, though the unit as experienced did not include some ideas about light and radiation (see Section 4.1). The activity itself was presented online as a single module (see Figure 6.1) and as a handout to guide students in the planning and design of the experiment, with an additional rubric for peer assessment.
Figure 6.1. The Sustainable House Inquiry task, as presented in the online module.

As a guided-inquiry, the students chose one of seven inquiry questions to investigate through their own experimental design. Two major changes from the earlier versions of the task involved the format of the final report and the support for group collaboration. The first version of the activity had been designed using a written response template with lined spaces for students to record their responses to the questions. The teacher, Sophia, indicated this approach constrained students’ expression of learning into a single mode, and was not aligned with the RCA. She commented: “we were kind of pigeon-holing them into writing…into a particular kind of amount of space to think”. Sophia re-designed the task by
removing all the lines, reducing it to one page of instructions, and allowing students more options to present their final assignment than just as a traditional scientific report (e.g., photo story with images, comic strip, iMovie, poster, PowerPoint). These changes provided students with more choice and enabled them to express and share their ideas through a range of representations.

The second change involved students generating their final report as a group. This decision was based on Sophia’s observation that students were producing almost identical reports as a result of doing the investigations in groups. Sophia introduced Google Docs, which allowed individuals to work on the same document concurrently. She provided a peer assessment rubric setting clear expectations to guide students’ collaboration and also allowed them to choose their own groups. Group collaboration was consistent with the DCog perspective in that members had a common and potentially productive history of working together and thus would be better able to share their respective cognitive and practical resources to complete the task (Hutchins, 1995).

Over three lessons, students planned, undertook, and enacted their investigation. Video-capture and VSRI were integral to understanding how students orchestrated their investigation through the multiple modes and media, including ongoing dialogue. The volume of dialogue around the tasks provided an opportunity to assess students’ level of engagement and reasoning through discourse. To understand the nature of their dialogue, I applied Mercer’s (2004) typology for discourse.

6.1.2 Assessing the nature of student reasoning

Contemporary perspectives view science education as an induction into the epistemic processes of knowledge construction (Driver et al., 1994; Lemke,
Following the socio-cultural perspective, learning science in school is a discursive process by which concepts and reasoning are learned through practical activities, social interactions and individual activities, using cultural conventions and tools (Driver et al., 1994; Mercer, 2004; Mercer et al., 2004a). Practical investigations are central to scientific knowledge building practices, incorporating dialogue and jointly executed tasks, enabling students to develop reasoned arguments (e.g., pose questions, formulate and reach a consensus about hypothesis, describe observations, reason about cause and effect, and summarise results) (Driver et al, 1994; Mercer et al, 2004a).

To understand the nature of student’s reasoning as they engaged with this inquiry task, I applied two frameworks: Mercer’s (2004) typology and the RCA reasoning framework. Mercer’s (2004) typology of student dialogue links the quality of students’ conversations during joint activities to improved learning and conceptual understanding in science (Mercer et al., 2004a), by coupling reasoning processes with patterns of discourse under three categories: disputational, cumulative, and exploratory. In disputational dialogue, there is a predominance of disagreement and individual decision making with few attempts to share resources, offer constructive criticisms, or make suggestions. Dialogue often appears as short exchanges of assertions and challenges. In contrast, cumulative and exploratory talk are increasingly collaborative and have stronger links to students’ reasoning and learning gains. In cumulative dialogue, partners build on each other’s ideas but offer no critique. They construct knowledge through accumulation. The dialogue often contains repetitions, confirmations, and elaborations. In exploratory dialogue, partners engage critically and
constructively with each other’s ideas. Statements are made for joint
consideration and challenges are justified, with alternative ideas offered.
Everyone actively participates and their opinions are invited and considered as
part of a consensus. Of all three types, exploratory talk is most strongly correlated
to improvement of subject matter knowledge and the ability to more effectively
participate in problem solving tasks (Mercer, Wegerif, & Dawes, 1999).

In developing the typology for quality of dialogue, Mercer (2004)
combined quantitative and qualitative methods to assess the interactions and
understand patterns and incidences of key words, enabling both inductive and
deductive interpretations. Two salient indicators included the length of dialogue
(i.e., as phrases and sentences) and the use of linking clauses (e.g., because, if, I
think, would, could), which are associated with reasoning and helped identify
exploratory sequences for justifying or modifying claims (Mercer, Littlejohn, &
Wegerif, 2004). Though I did not perform a quantitative analysis, these indicators
were useful references.

In addition to identifying dialogic patterns to indicate reasoning processes,
I was also interested in the informal and formal reasoning processes that
characterise RCA. Tytler et al. (2013c) identified important differences in
reasoning processes for knowledge construction and those for the justification of
ideas. The latter involves those that are traditionally associated with scientific
methods and report writing: the use of formal, logical, and linguistic approaches
(e.g., deductive, inductive, abductive). For the more imaginative and tentative
activities of discovery and knowledge construction, a range of representational
resources are involved in the development of explanatory accounts, including use
of informal processes such as perception, metaphors, and analogies.
To show how both play a role in knowledge construction, Tytler et al. (2013c) proposed a framework organising reasoning processes around a representational challenge. These involve three key moments of reasoning: explore, construct, justify – each involving a specific pattern of reasoning.

Exploration involves observations and pattern recognition through mapping the referent with representations. Construction involves interpretation of observations and patterns with ongoing negotiation and refinement of representations. Justification involves public sharing and application of ideas. In many ways, the design of the inquiry task in my study reflected an elaborate representational challenge, requiring students to generate and coordinate representations to support a conceptual claim (Tytler et al., 2013a). In relating these three moments to the planning, experimental, and report writing stages of the inquiry task, I identified patterns in students’ reasoning processes. I assessed their engagement with the discursive practices of science and the quality of the learning, drawing on evidence from their dialogue (see Episodes 1-16), interactions with representational resources, and progressions in conceptual understanding.

6.2 Students’ Engagement with the Task: Planning

The first of three lessons was dedicated to the introduction and planning of the task. Sophia spent the initial 30 minutes introducing the task and giving suggestions. Students received the Sustainable House (SH) Inquiry handout based on the online information (see Figure 6.1), the peer assessment rubric, and milk cartons (i.e., model houses). Sophia explained each of the seven inquiry questions, elaborating on possible experimental designs, along with the role of dependent, independent, and control variables. During this whole-class discussion, Sophia referenced Inquiry Questions 2 and 3, suggesting both could
be combined into a single experiment with two independent variables: foil inside and foil outside. She stated: “keep every other variable controlled”, including time and distance of heat lamp. The information shared through the whole-class discussion and resources provided important scaffolding for this guided inquiry task and influenced the case group’s choices. The remaining 45 minutes of the class was dedicated to planning. Like many of the other students, Ina, Megan, and Clara continued to work together as a group for this task. Using their SH handout and inquiry questions to guide them, the case group engaged in a discussion about their hypothesis, method and materials, and roles and responsibilities, to come to a consensus about their ideas.

6.2.1 Developing the hypothesis around the inquiry questions

Though students were only required to address one inquiry question, following the example that Sophia highlighted during her introduction to the activity, the case group chose the following two questions: Does foil inside a wall keep a room cool in summer? Is foil inside a wall just as effective as having foil outside a wall? They had just begun discussing their design when the teacher reminded the class that the task would require them to work together, particularly for the report, and recommended using Google Docs for this purpose. They resumed their conversation, but Megan suddenly excused herself to go to the washroom. While she was gone, Ina and Clara continued the conversation and focused on their inquiry questions, with Ina initiating the writing of the questions in her project book and Clara following suit. The conversation between Ina and Clara continued for over two minutes as they discussed what might happen in each of the scenarios (Episode 1).
1 Ina: ... I reckon that foil inside the room...Actually I don’t know, to be honest.

2 Clara: Yeah, because like...

3 Ina: Inside...Maybe once its inside it already hot. If you know what I mean. Like maybe it’s gotten through so it’s already hot.

4 Clara: When its inside its keeping heat in...OUT [gestures]!

5 Ina: No, but I thought...Because maybe it’s like [grabbing the carton]. but if its inside, it means the heat is already in [orienting the carton to demonstrate]. But it would have that gap. Not the gap...the gap if that makes sense.

6 Clara: Where’s the gap?

7 Ina: Let’s take this here [grabs the mic] ... 

8 Clara: I think if the foil is inside [demonstrates with carton] ...

9 Ina: Hang on, I need to untangle the mic...

10 Clara: OK if the foil is inside, then the lamp is like shining here [places clenched hand into carton], shining towards the house, the foil will prevent the heat...

11 Ina: Wait! Will this be on one wall ...or all the way?

12 Clara: All the way inside.

13 Ina: I reckon, if it’s on the outside, it might just heat up.

14 Clara: Yeah, so...

15 Ina: Because if it’s on the outside, it might heat up and then put it in.

16 Clara: Maybe they are the same.

17 Ina: Yeah, they might be the same.

18 Clara: Yeah, they might be the same [looking into the camera].
19 **Ina:** But it’s easier for the hypothesis if you pick one, you know...
[short pause as Ina looks at her project book].

20 **Clara:** Oh no, it’s like, cause like if the foil is outside, it will attract the heat to the house.

21 **Ina:** That’s what I thought [gestures to support the ideas of foil attracting the heat].

22 **Clara:** It would absorb the heat. But if it’s inside, it will [gestures].

23 **Ina:** Yeah, if it’s inside [gestures]. But that’s kind of assuming, but like....

24 **Clara:** Yeah. We’ll just stick with this.

25 **Ina:** Let’s write that down...
[A few seconds later the conversation oriented back to their hypothesis]

26 **Ina:** We’ll say: foil on the inside would be helpful to keep it cool...

27 **Clara:** Yeah.

28 **Ina:** But we might be able to say, but its better if it’s on the outside.

[Ina and Clara are writing in their project books].

In developing their hypothesis and predictions, Ina and Clara indicated foil inside would keep “heat in” (line 4) through a “gap” (line 5), “the foil will prevent the heat” (line 10), and would also keep the house cool (line 26), consistent with ideas about insulation. However, their ideas about the foil outside were conflicting: they postulated “absorb the heat” (line 22), “attract heat to the house” (line 20), and the house “might just heat up” (line 13).

In addition to their exchange of ideas, their dialogue included phrases such as *I reckon* (lines 1, 13), *I think* (line 8), *because* (lines 2, 15), *maybe* (lines 3, 16), which were key indicators for exploratory dialogue. During their dialogue,
student also manipulated the carton and used gestures as they explored and clarified their ideas and made claims. Ina spontaneously brought the carton into the conversation as she was describing the results of having the foil inside (line 5), then Clara took the carton and directed the conversation towards the position of the lamp (line 10) (see Figure 6.2). They used gestures to clarify ideas, such as when Clara claimed the foil on the outside would attract the heat (line 20) and Ina supported her idea with more amplified gestures (line 21) (see Figure 6.2).

![Figure 6.2. Clara demonstrated the how the light will shine down on the carton (left) and Ina used gestures to show how foil on the outside attracts heat (right).](image)

Their gestures reflected students’ spatial reasoning about the movement of heat and demonstrated how they supported each other’s ideas about the effects of light and heat (Goldin-Meadows, 2014, 2016). However, their ideas about heat being attracted to the foil outside the house were inconsistent with the canonical views. Both Ina and Clara recorded the inquiry questions into their respective project books and by the end of this part of their discussion, Ina recorded the “dot points” to clarify their hypothesis, summarising their ideas in the written mode (see Figure 6.3).
In addition to their two inquiry questions, Ina recorded their predictions:

“foil outside might attract heat rather than repel it? Foil on the inside could possibly create a barrier? ‘Just as effective’ having the foil outside is effective, but is it effective on the inside?” Ina wrote these as questions instead of statements and included vague terms (i.e., might, could, but), suggestive of the tentative nature of their ideas. Although these questions did not commit them to a prediction or hypothesis, they helped consolidate the students’ thinking during the planning phase and were referenced during the following lessons as they revisited their original ideas. As Ina and Clara continued deliberating if the foil inside was as effective as the foil outside, Megan re-joined the group and asked them to explain what they were talking about. Megan emphasised the need to “still do all the tests” for comparison, and Ina agreed.

Near the end of the lesson, after the case group addressed their method, materials, roles and responsibilities, they returned to their hypothesis. Ina summarised: “…we decided together that outside would be more effective because it’s on the outside, it’s pushing the outside light away.” Her explanation indicated they had abandoned their previous ideas about foil absorbing or attracting the heat, showing a shift in their understanding, though they were still describing the process in informal terms (i.e., pushing).
In developing their hypothesis, the case group engaged in exploratory dialogue using gestures and the model house as they explored their ideas and predictions for both scenarios, integrating these transient or ephemeral representations across verbal, visual, and actional modes. Though they eventually fixed their ideas in their project book in the textual mode, they wrote them as questions, suggestive that their ideas were not yet resolved. Ina’s summary comment provided some clarity to their ideas, however, as a verbal explanation it resulted in some uncertainty as they conducted their experiment the following lesson.

6.2.2 The method

In negotiating the method for the task, there were a few false starts about whether to address the aim, use Google Docs for the report, develop the hypothesis, discuss their responsibilities, or write the procedure. Their conversation eventually oriented around how to set up their variables and trials (Episode 2).

1 Ina: Well, so...Method! [begins writing]. Well, we’d have three? So one outside [counting with fingers], one with the foil outside, a control...

2 Clara: One... [Picks up carton]. We have two...[Megan takes the carton from Clara]

3 Ina: Three!

4 Clara: We’ll get three milk cartons [taking the carton back from Megan].

5 Megan: We need to remember [pointing to the SH handout] we have one with foil inside. We need to have foil inside...

6 Ina and Clara: [Simultaneously] Outside and control.
7 Megan: Because the reason we need control is for Question 2.

Episode 2 showed students building on each other’s ideas through cumulative dialogue as they established the need for three cartons with one variable: foil outside, foil inside, and a control with no foil, using the SH handout as a prompt. They continued to discuss the number of trials and clarified the need for a control group (Episode 3).

1 Ina: OK, but how many times are we going to do each one?

2 Clara: Three!

3 Ina: Three? Yes. Oh wait! Do you need to do three for control though? Cause then you can get the average.

4 Clara: Yeah.

5 Ina: That’s like more method though.

6 Megan: Three trials [playing with the carton].

7 Ina: So, method! [Writing in project book] What’s step one?

8 Megan: OK, so step 1: Set up equipment! [Slamming the carton on the desk to emphasise the steps, looking at Ina]

9 Ina: You can’t just write that [gesturing]. If someone looked at our methods, or set up the equipment, they wouldn’t just go, ‘oh ok’ [looking at project book and gesturing],

10 Megan: Ok, first thing you do… Do we need 3 lamps? [With both hands tucked into the carton]. Do we want to do three things?

11 Ina: We will probably have to do it separately because there’s not enough lamps.

These exchanges showed the dialogue was largely cumulative as students deliberated over the details of their method using gestures and models (see Figure
They decided on doing three trials and determined they could calculate the average between them (line 3). Their conversations around the method, variables, and trials demonstrated they were integrating scientific terminology and conventions as part of their epistemic engagement in the task.

In the VSRI, Clara elaborated on having three trials: “We needed…we thought that having three would be a good average. We would get really good results out of it, but then since it was Tuesday, there wasn’t enough time and with the assembly going on [of the cartons] that didn’t happen so we only got two tests in.” Ina confirmed: “We wanted to do three, but there wasn’t enough time”.

The case group was aware that multiple trials supported better results, indicating an understanding of reliability in scientific investigations.

Figure 6.4. The case group engaged with different representations in Episode 2 (left) and Ina used gestures to explain an idea in Episode 3 (right).

The dialogue around the method was supported primarily by general conversational gestures (i.e., without a conceptual purpose), with the carton as incidental (see Figure 6.4). Whereas the exploratory dialogue around the hypothesis involved representational resources (e.g., gestures, models) to enlist scientific concepts to make claims (Tytler et al., 2013b). The cumulative nature of the dialogue also demonstrated how the group finalised the details of their method together. Whereas students traditionally follow the step-by-step procedures
provided in a practical investigation, the case group was required to reason about their hypothesis and method, draw on their collective ideas, and come to a consensus to complete the task.

Their final discussion in this lesson was prompted by Ina’s question to the teacher: “What do you have to have done before you do the prac?” Sophia clarified they needed to complete the title, hypothesis, equipment list, and method by the next lesson, adding that students could still make some changes to improve their ideas on the day of the experiment. Sophia then announced to the class that there were 10 minutes remaining in the lesson, and because the day of the experiment was during the shorter lesson (i.e., 60 minutes), that they have most of their planning completed prior. In response, Ina, Megan, and Clara immediately began to call out what they wanted to do, volunteering, delegating, and negotiating for tasks, with fast-paced shorter exchanges and sudden shifts in decisions. As this was going on, Ina was also recording their planning ideas in Google Docs, which she sent to her group at the end of the lesson. Their engagement in this task was evident through their interest in sharing responsibilities and completing the requirements for the planning lessons. By the end of the planning stage, the case group had: selected their two inquiry questions; developed their method using a single variable as the position of the foil inside and outside the carton, along with a control; listed their materials; and determined their roles and responsibilities to prepare and undertake the investigation.
6.2.3 **Summary of the planning stage**

**Inquiry-based learning**

The guided inquiry-based task provided students with enough scaffolding to direct them through the task and enough flexibility to engage them more directly in the epistemic processes. This was a shift from more procedural or step-by-step approaches to practical investigations (Abrahams & Millar, 2008). Students chose their inquiry questions and developed their hypothesis and experimental design (e.g., method, materials). This required collaborative dialogue around ideas, questions, predictions, decisions, and the refocusing on the key points. The case group engaged in exploratory and cumulative dialogue during the planning stage. Exploratory dialogue was associated with reasoning through models, gestures, and dialogue. Cumulative dialogue was associated with decisions around their experimental design, particularly identifying the variables and controls, and deciding on the number of trials to support reliability.

**Reasoning with representations**

Through exploratory dialogue, students’ conceptual ideas were distributed, developed, and refined through key representational resources in the planning stage. The distributed cognitive system included gestures, project books, the SH handout, the model house, and Google Docs (Zhang & Patel, 2006). Applying the RCA reasoning framework, the planning stage primarily involved exploratory reasoning about their hypothesis, involving informal reasoning around observations, and tentative explanations as the students focused their attention on the two treatment groups, experimenting with possible scenarios. They initially postulated that foil on the inside would prevent the heat from getting out and would be helpful to keep the house cool (see Episode 1), and foil on the outside
might attract or absorb the heat, causing the house to heat up (see Episode 1 and 2). In exploring their ideas, they enlisted gestures (i.e., action) and models (i.e., visual), fixed through the written word (i.e., textual), then refined again during their final conversation (i.e., verbal), as they engaged in multimodal semiotic meaning-making processes. Each representational form presented a specific affordance: the SH handout prompted students’ dialogue; the model house was manipulated through gesture and focused their ideas around the spatial positioning of the foil and probe; gestures activated students’ spatial reasoning about radiant heat pathways and indicated how they supported each other’s their ideas about the effects of light and heat.

By the end of the planning lesson, the case group indicated that both tin foil on the outside and inside would be effective in keeping a room cool in summer, but more effective on the outside because “it’s pushing the outside light away”, indicating a departure from their initial ideas about foil attracting or absorbing the heat. Despite students’ conceptual progression, their final written predictions were written as questions, and their final hypothesis statement was expressed verbally, suggestive of a tentative conceptual understanding by the end of the planning sessions.

6.3 Students’ Engagement with the Task: The Experiment

The second lesson of the series was dedicated to the experiment and featured the datalogger, a specialised scientific tool that generated real-time data tables and graphs. At the beginning of this 60-minute lesson, the teacher briefly reviewed the peer assessment protocol and the laboratory report template from Google Docs. While Sophia was explaining the laboratory template in Google Classroom, she identified key features including the title page, introduction,
hypothesis, tables for results, conclusion, and references. In their respective project groups, students finalised their plan and began their experiment: collecting the materials, setting up, and then conducting their experiment. By the end of this lesson, all groups completed their data collection. Some groups had begun drafting their final report as they undertook the experiment, while others did this after completion or during the next class.

The datalogger was a dynamic representational resource used to automate the task of collecting temperature data and converting it to a graph (Rogers, 2008; Zhang & Norman, 1994; Zhang & Patel, 2006). Instead of students physically performing the task of reading the temperature, recording the data, and translating the data to a graph, they had only to focus on the visual representation of the real-time graph. The immediacy of generating a graph engaged students in reasoning about the ongoing results.

The case group organised their experiment as consecutive trials of the control, foil on the outside and foil on the inside treatments. To better understand students’ progression of ideas through this subtask, I organised this section into four stages: equipment and set up, first set of trials, second set of trials, and the summary of results. Similar to the previous lesson, each of these stages demonstrated students’ engagement with the inquiry requirements of the task. There was however, a chaotic progression of conceptual ideas as students interpreted and processed the results generated by the datalogger.

6.3.1 Equipment and set up

The case group completed their planning prior to this lesson so they immediately began gathering their materials, setting up the trials and datalogger, and conducting their experiment. Students shared tasks as they set up their
experiment: Megan collected the materials as Ina assembled the datalogger and probes; then Megan and Clara prepared the materials (e.g., cutting the foil, building cartons) while Ina programed the datalogger. Because of the shorter lesson, the case group decided to do two trials for each group. I noticed they had turned on their lamp while they were still setting up the equipment so reminded them to keep it turned off until they began their trials. Ina was experiencing some challenges programing the time interval of the datalogger to five minutes and asked Sophia for help. Sophia asked if they wanted three or five minutes and Megan indicated they would only have time to do three-minute trials (i.e., 180 seconds). When Megan asked how they would collect the data from the graph generated by the datalogger, Ina pointed to her project book, where she would record the data, and also suggested they take a photo of the graph. From the start, the students demonstrated cooperation, with each taking the lead on different tasks, clarifying their procedures, and making final changes. Over the next 20 minutes they conducted and completed their trials.

6.3.2 First series of control, foil outside, and foil inside trials

The case group began with the control trial, using the empty milk carton, while constructing their model houses for the following trials (Episode 4).

1 Ina: It started at 23.4 and now it’s at 23.8 [reading off the datalogger] and we’re nearly finished. So, it hasn’t gone up by a lot. Not at all...23.9! So it hasn’t even gone up one degrees yet [looking at the datalogger]. Is it gonna...we have about 30 second left of the time and it hasn’t gone up one degrees yet.

2 Clara: One degree [correcting Ina].

3 Ina: One degree. Maybe it will do it...
4 Megan: I’m done! One whole box [holding up the milk carton she just finished assembling]!

5 Ina: Well that’s all you need so that’s good [high fives Megan].

6 Megan: …Um does that mean I’m not doing the same…Are we going to use the same foil…

7 Ina: Yeah, we should…um…Look [staring at the datalogger]! Its finished [pointing at the datalogger graph which was now completed and turning off the lamp]!

8 Clara: Ok.

9 Megan: We have to do the next one!

10 Ina: Its finished. OK. So now…wait! Record it. Take a photo. Can you get your computer [motions to Megan to get the camera interface from her laptop]?

11 Megan: The camera doesn’t work.

12 Ina: I’ll take it on my phone [Clara briefly covered camera screen while Ina took a photo].

13 Clara: OK, so now we wanna…

14 Ina: OK I need to write it down [looking at the datalogger]. It doesn’t tell you, how do you look at it [trying to interpret the graph]?

15 Clara: Ok. So 23.9.

16 Ina: OK so is that the temperature [pointing at the datalogger]?  

17 Clara: I think that’s the temperature right now.

18 Ina: Wait, so how do you… [trying to determine the temperature from the datalogger and pressing the buttons on the screen] …What [throwing
up her hands in confusion and holding her temples, then pressing the
data logger buttons again]?! 

19 Clara: So, it was 23.2, now its 24.

20 Ina: [Repeats these numbers as she is writing in her project book].

21 Clara: 24. Can you see? Can you see how it goes from there to there
[explaining how to read the temperature from the data logger]?

22 Ina: Yeah. Do the next one.

Episode 4 provided information about how the group was sharing tasks to establish their procedure and interpret the data logger. The students demonstrated cooperation, with Ina and Clara monitoring the data logger while Megan was constructing milk cartons for the following trials (see Figure 6.5). Their dialogue was largely cumulative, building on each other’s ideas as they established their procedure, supporting each other’s tasks (lines 5, 21), and solving problems (line 12). By the end of the first control trial, students also established their key representational resources for the experiment: dialogue, gestures, project book, scientific apparatus (e.g., lamp, model house), iPhone camera, and data logger, along with their procedure. See Figure 6.5 for the experimental set up for the control trial, including the data logger and the position of the heat source outside the house.

Figure 6.5. The case group’s set up of the first control trial (left) with the data logger on the bottom right hand side of the photo (right).
Though students were introduced to the datalogger in Module 6 (see Chapter 5), Ina seemed tentative with this technology during this first trial (line 7, 18). The functionality of the datalogger to print, save, and send was not operational so students also had to improvise by taking a photo (line 12), recording the data by hand in their project books (line 20). With the sudden realisation that Megan’s laptop camera did not work (line 20), Ina used her own iPhone to take a photograph (line 12). Though she showed some reservations about the datalogger, she was confident with integrating her own technology as an immediate solution to a problem, suggestive of students’ inclination towards implementing technology when problem solving.

Though students were more focused on operating and reading the datalogger during this first trial, they experienced the broad affordances of this digital resource. The real-time display prompted immediate conversations around the increasing temperature and establishing their procedure, demonstrating student engagement with the inquiry processes. Students were also learning to relate the material phenomenon of temperature increasing with the graphical representation, and re-representing the data into a data table, engaging in semiotic meaning-making processes (Ainsworth, 2006; Rogers, 2008). Though there were no examples of conceptual reasoning in this episode, students’ meaning making was distributed across the physical (i.e., scientific apparatus), digital (i.e., datalogger), representational (i.e., graph, data table), and communication (i.e., dialogue) spaces, as a cognitive system of meaning making throughout the task (Rogers, 2008). These interactions became more pronounced and elicited deeper conceptual reasoning and engagement as students became more proficient with the tools in the following trials.
Foil on the outside trial 1

The case group quickly transitioned to the next trial, with the foil on the outside of the carton. They were more confident with the datalogger and once they noticed a change in the graph, engaged in an exchange about the concepts of reflection and radiation based on the initial results of the generating graph (Episode 5).

1 Megan: How many trials are we doing of each?

2 Ina and Clara: Two [as Clara was assembling another carton]!

3 Ina: It’s because there’s not much time...although I guess...

[Indistinguishable]

4 Ina: Is it going down [looking at the datalogger]?

5 All: Yeah [looking at the datalogger]!

6 Ina: Slightly...

7 Megan: I thought the light...

8 Ina: The idea is that the foil pushes it [gestures].

9 Clara: It reflects the....

10 Ina: We don’t really want it to get hot.

11 Clara: Yeah.

12 Megan: Because it’s supposed to be cool.

13 Sophia: [Announces to class] You’ve got about 20 minutes, girls. Twenty minutes to take your data.

14 Clara: I think we would have enough time [still assembling the carton].

15 Ina: Yeah. And if we have more time, we can do three.

16 Clara: Yeah.
In Episode 5, the graph generated from the datalogger stimulated students’ dialogue as their attention constantly shifted from the real-time readout and their interpretive discussion. Upon noticing the temperature decrease (lines 4-6), they began constructing a joint explanation (lines 8, 9) based on the model of the summer house (lines 10, 12). Their joint construction of knowledge and consensus building were indicative of cumulative dialogue, as they were relating the initial results with their predictions. Prompted by the teacher helper who was looking in, Ina reiterated their prediction: “Well our theory is that the foil on the outside will protect the inside from the heat. It’s doing what we wanted.” She presented their prediction as a statement, contrasting with their earlier ideas which were presented more tentatively as questions. This was their first shift in expressing their understanding of reflection.

The students also continued negotiating the number of trials, still hoping to do three trials though aware that the time constraints would limit them to two. Their consideration of the design demonstrated their ongoing engagement with the task and their awareness of the importance of carrying out a higher number of trials in an experiment.

After the teacher-helper left, Ina and Megan continued to watch the final seconds of the generating graph for the first foil on the outside trial, while Clara constructed the next carton (i.e., foil on the inside) (Episode 6).

1 Ina: It’s going down!

2 Megan: Yep. Cause I think the heats bouncing off the reflective…. 

3 Ina: [Gestures how heat bounces off surface].

4 Megan: ... surface.

5 Ina: That’s what we wanted.
6 Clara: That’s what we predicted and -

7 Megan: We’re almost done and we gotta really quickly put the next one in.

8 Ina: So, the temperature went from 26 to 23 [reading off the datalogger, then leaning over to turn off the light]. So, the temperature went from what [pointing to the datalogger with her pen and shifting toward her project book]?  

9 Clara: [Reading off the graph] 24.6.

10 Ina: To what [writing in project book]?  

11 Clara: To 23.9.

12 Ina: OK, right. Take the photo [retrieves her iPhone].

13 Clara: [Speaking into the mic] So the result of the foil being outside the carton box thingy was what we predicted, like, it would reflect the heat.

Episode 6 showed a continuation of the cumulative dialogue centred around the final seconds of the generating graph. Their ideas were more refined and elaborate compared to those expressed at the beginning of the trial, with Megan offering a more thorough explanation (line 2), Ina supporting her comments through hand gestures indicating the bouncing of rays (line 3 and see Figure 6.6), and Clara summarising the final results in a statement (line 13).
Figure 6.6. As Megan explained how heat bounced off the reflective surface as Ina gestured.

During this trial, students demonstrated a progression of conceptual understanding based on the real-time results of the generating graph. The case group initially predicted the house would stay “cool” because the foil would “push” or “reflect” the light to “protect the inside from the heat” (see Episode 5 lines 12, 8, 9, 20). Megan then elaborated on the mechanism: “I think the heat is bouncing off the reflective surface” (see Episode 6 lines 2, 4), supported by Ina’s gestures (see Figure 6.6) and confirming their prediction (see Episode 6 line 6). Their explanation progressed from a more general statement related to their prediction: “the foil on the outside will protect the inside from the heat” (see Episode 5), to “the result of the foil being outside the carton box…would reflect the heat”, which included a causal mechanism (see Episode 3 line 13). By the end of their first trial, the case group clearly stated their prediction, used the evidence from the trial to support their prediction, and provided a mechanism using the correct scientific terminology (i.e., reflection).

With increased confidence in their procedure and in operating the dataloggers, the students proceeded to engage in conceptual reasoning to interpret the results. The immediate feedback from the datalogger enabled them to interpret the data and share their ideas concurrently without having to wait until the end of
the practical investigation when they are consolidating the data. Their initial observations of the decreasing temperature elicited more informal deliberations, while their later observations included more elaborate causal mechanisms. Students were now linking conceptual ideas across the physical, digital, representational, communication spaces, which continued through the remaining trials in varying degrees (Rogers, 2008).

Foil on the inside trial 1

The students quickly transitioned the next trial, using their third model house with foil on the inside, maintaining the same setup with the heat sources outside the house (Episode 7).

1 Ina: Look how good it’s going [pointing to the datalogger showing the increasing temperature]. This is what you want for winter.

2 Clara: Yeah.

3 Megan: But this is for summer.

4 Ina: So half of this is not really working...

5 Clara: Yeah.

6 Megan: Well it is working, it’s just not...

7 Clara: Cause we thought that both of the...

8 Ina: Yes.

9 Clara: We thought that umm...

10 Ina: They’d both be the same.

11 Clara: Umm...

12 Ina: No, we didn’t, we thought this would be worse.

13 Megan: No, we thought this would be hotter.
14 Clara: Let’s see our hypothesis [learning over to get Megan’s project book].

15 Megan: I haven’t written the hypothesis yet.

The real-time results from the datalogger elicited confusion amongst the group. Ina based her observation on a model for winter (line 1), and Megan clarified it was for summer (line 3), indicating they were still unclear about their model. When Clara suggested they review their hypothesis (line 14), it became known that Megan had not yet written it (line 15), suggestive of their awareness for the need of a written hypothesis to reference their ideas. By the end of this trial, the case group noted that the temperature increased very quickly, though they did not resolve their confusion around their predictions. Discussion around the mechanism did not take place until the second trial. They proceeded with the trial and focused their conversation around how to organise the data for all three trials (Episode 8).

1 Ina: Are we going to record this part? Because I’ve written what it was to what it went to [pointing to her project book]. But how are we going to write in the actual thing?

2 Clara: It’s just like [gestures]...

3 Ina: Just the final answer.

4 Clara: Yeah...

5 Ina: We have to do an average.

6 Clara: Uh huh.

7 Ina: I know how to get an average because there are two things.

8 Clara: Yeah, like you need to record how much it went up by...
Now confident with their results, students discussed calculating the average difference between the two numbers (lines 4, 6), demonstrating their continued engagement with the overall task. By the end of this first series of trials, students established their procedure, gained confidence operating the datalogger, were translating the graph to their data table, and participating in ongoing discussions around the results and approaches. They were relating the results with their predictions, though their predictions were unclear and their hypothesis was unresolved. The second series of trials provided them with information from which to compare these initial results.

6.3.3 Second series of control, foil outside, and foil inside trials

As the case group began the second trial for the control house, all three students were closely watching the datalogger and commenting on the initial results (Episode 9).

1 Clara: So this is our second trial of our control and it's [speaking directly into the microphone]...

2 Megan: And it’s staying constant!

3 Clara: ...it’s constant.

4 Ina: That’s good!

5 Clara: So much the same as our first trial. So that’s good.

This short episode highlighted students’ anticipation of a constant temperature, consistent with the results with their first trial. Confident with the generating results, the students engaged in a conversation about the overall experiment so far (Episode 10).

1 Ina: It’s going right like our hypothesis says.

2 Clara: Yeah.
3 Megan: Excellent!

4 Clara: So we predicted...

5 Megan: You know what I think the thing will be about... It will be about how much its risen, instead of like what temperature it gets to.

6 Ina: Yeah.

7 Megan: Because I’m noticing that this is a lot higher [pointing to the datalogger] than the first time we did it.

8 Ina: But it’s about how...

9 Megan: But I think that just because it’s already like heated up [pointing to the carton]...

10 Ina: It’s about how much it goes up, not...

11 Megan: I think it will be about, yeah, comparing the two temperatures, you know.

12 Ina: Yes. Well the one with the foil on the inside is like... insulation.

13 Megan: Yes.

14 Ina: Inside. The foil is like...insulating...Is it finished [looking at the datalogger]?

15 Clara: Conduction!

16 Ina: What did it go up from?

17 Megan: Yes! Take a photo.

18 Ina: What did it go up from [as she takes her iPhone out of her pocket]?

20 Megan: 25.5 to 26 [as Ina writes in her project book and Megan takes a photo, then Ina inserted a temperature probe into foil covered carton trial].

As the graph was generating the predicted data, students engaged in cumulative dialogue about temperature differences and the mechanism to explain the foil on the inside results, sharing and building on each other’s ideas. Megan noticed the temperature was already higher from the last trial (lines 7, 9) and commented on the temperature differences (line 5). Ina stated that insulation was the mechanism to explain the increasing temperature on the foil on in the inside trial 1 (lines 12, 14), and Clara threw in the term “conduction” (line 15), which was not taken up in the discussion.

Foil on the outside trial 2

Students proceeded to work together to set up the next trial, foil on the outside. Ina inserted the temperature probe and positioned the house in front of the lamp. Megan pointed out that the house was not the same distance away from the light so they re-adjusted its position, reminiscent of the advice given by the teacher during the Planning lesson. The students all yelled out “Go!” as they turned on the lamp and began the datalogger as a coordinated team. They discussed the possibility of doing another trial if they had time, then suddenly noticed that the temperature immediately began going down. As the datalogger continued to measure the temperature, they became distracted and broke out into song, but mid-way through Ina interjected: “look how much it’s going down!”, indicating she was still attending to the task. She also announced there was exactly “100 seconds left” for this trial and asked the teacher how much time was left in the class, another example of her taking the lead during this activity. Clara
inquired if they had enough time and Ina confirmed they only had to do to one more. Though their confidence in the datalogger seemed to elicit both constructive and off-topic interactions, they continued to attend to the task, evidence of their continued engagement.

|During the VSRI, Ina reflected on their initial ideas during the planning stage where they indicated the foil might attract or absorb the heat, which contradicted their actual results: “We thought that, we still sort of thought foil would get hot. Even though that’s still not scientifically what’s going to happen, but we still sort of thought that’s what going to happen even if the temperature actually dropped.” I asked the students to elaborate on why their ideas changed, and Clara responded: “We did on the STILE app, I remember this video about sustainable housing if you put like reflective shiny things on the top of your house, it would bounce off.” Megan added: I thought that the light was hitting the foil and it’s bouncing off in a different direction. Cause like, I have a tin like roof at my house, and it stays pretty cool mostly.” Ina’s comment pointed to the difficulties of changing alternative conceptions, despite having the scientific knowledge. Clara’s comments demonstrated the impact of the STILE information on her, as she referenced information as a possible explanatory model to help her make sense of the results. Both comments indicated students were reflective about the results of their foil on the outside trial and attempted to relate them to prior experiences, re-examining their ideas as part of their meaning-making practices. |
Foil in the inside trial 2

With 10 minutes left, the case group commenced the last trial, foil inside the house. The initial results were not what they expected (Episode 11).

1 Ina: What’s it doing? It’s not going up [looking at the datalogger]. Um this hasn’t got foil – oh yeah it does.

2 Megan: Yes it does. Is there foil along here [pointing]? Its fallen down?

3 Ina: Why is it going down?

4 Sophia: [Announced to class] You can leave your boxes assembled if you like...

5 Ina: It’s not doing the same thing. Now, it’s going up [looking at the datalogger].

6 Clara: It’s going down.

7 Megan: Oh, that’s excellent [sarcastically].

8 Clara: It shows that how insulation...no - that’s conduction...

9 Ina: Because its [the foil] fallen down a little bit. Maybe because its fallen down a little bit, it’s not doing it.

10 Clara: Yeah.

The initial result of this trial elicited confusion as students were anticipating the temperature would increase as it did during the first trial. They deliberated if it was the right house or if the foil had fallen down, sharing each other’s ideas through cumulative dialogue. Clara attempted to offer a scientific explanation, but confused insulation with conduction (line 8). In this Episode, students’ ideas were disrupted by the real-time results, which prompted them to construct alternative explanations. With only a few minutes left in the lesson, the temperature began increasing (Episode 12).
**1 Ina:** OK, wait. Why does it go down first [looking at the datalogger]?

**2 Clara:** [Announced into the microphone] Our results are really strange. It has gone down first and then gone back up again [focusing the camera on the datalogger].

Clara commented that the results were strange because the temperature went down before increasing (see Figure 6.7).

In the VSRI, Megan reflected on the initial decreased temperature of the second trial: “I think it was adjusting from the previous temperature that it had been on. It was just like, I really think we should have left everything to cool down before we did it”, providing a plausible explanation for this anomaly, consistent with her comments in Episode 10 (line 9).

Figure 6.7. Graph generated by the datalogger showing a decrease (left side of graph) then an increase in temperature (right side of graph), with a close-up view (right).

The datalogger provided students with immediate visual data, which enabled them to more easily identify trends and changes, and to then compare across previous trials (without even having to reference the previous image of the graph). The data output was also keeping up with their ideas as expressed through their dialogue. Compared with the longer time interval (e.g., minutes, hours, days)
required to read, record temperatures, and then translate to a graph, the digital technology allowed for immediate dialogue around the results. As this was the last trial for their experiment, the case group disassembled their experiment, returned the equipment, and returned to their desks.

Summary of results

Ina and Clara summarised the results, reading off Ina’s data table in her project book (Episode 13).

1 Clara: So the results show us that the control was consistent [focusing the camera on that section] – mostly consistent. And it didn’t go up by...

2 Ina: It went up.

3 Clara: It went up by point 5. Like a half a degree [showing results table in the project book].

4 Ina: And the foil on the outside...[focusing the camera on that part of the table]

5 Clara: They went up, yeah. It went down. The foil on the outside went down because maybe they don’t attract to the heat and it reflects the heat.

6 Ina: So the foil inside...interesting results.

7 Clara: Yeah, very interesting results.

8 Ina: It began to go down at the start.

9 Clara: For our second trial [pointing at the part of the table], it began to go down for a while, like maybe 2 seconds. And then it went back up. So that’s interesting.

10 Ina: But it’s still gone up.

11 Clara: Yeah, by a degree [still pointing at the data table].
12 Ina: That’s our results so we’ll be able to write that up because it does support...

13 Clara: Our hypothesis and what we predicted. So that is a very good result.

Episode 13 provided information on how Ina and Clara were making sense of their results in relation to their hypothesis. Students built on each other’s ideas, initiated, and finished off each other’s sentences as cumulative dialogue. For the control trials, Clara described their results as “mostly consistent” (line 1), with just a half degree increase. For the foil on the outside trials, Clara noted the temperatures went down and attributed these results to the foil reflecting the heat, instead of attracting it, consistent with their progression since the planning stage and Episode 5 and 6. For the foil on the inside trials, Ina noted that the temperature initially decreased at the start, and then Clara reported that it went back up. They were reading from Ina’s project book, though Megan had also recorded results in her data book (see Figure 6.8).
The data tables illustrated how each student re-represented the temperature from the graph. Ina was more actively involved in managing and orchestrating the investigation, so her table was very simple. Although it seemed that Megan played a more minor role in interpreting the generating graph, she was recording more substantive information in the data table, calculating the temperature
differences. Megan’s more elaborate data table might have been associated with her observations around temperature differences in Episode 10. Both examples demonstrated that students were actively engaged in the task and incorporating representations that were most meaningful for them.

During the summative inquiry task, students spontaneously incorporated gestures and models to develop their hypothesis, and created two different kinds of data tables to translate the results of the generating graph. They then translated one of these tables into a collaborative summary of findings. Both examples suggest a high level of representational competence through their spontaneous application of representations and their ability to relate representations across modes. For their summary, Ina’s data table functioned as a prompt for dialogue and consolidation of ideas. Students re-represented the data generated from the graph to the data table, and again through their explanation of the overall patterns of temperature differences and related them to their hypothesis, engaging across multiple modes for meaning making.

6.3.4 Summary of the experiment stage

By the end of this 60-minute lesson, the case group completed two series of three trials to investigate both of their inquiry questions. All three students participated in the planning and experimental stages and seemed motivated to undertake and complete the task, evidenced through the quality of the dialogue and interactions with both digital and non-digital technologies throughout. Applying the RCA reasoning framework, the experiment stage involved an interplay of constructing, refining, justifying, and critiquing ideas through representations. This stage also involved students engaging in both informal and formal reasoning processes as they explored their ideas through interpretation of
data and translation across representations, and more confidently justified their claims. Students’ observations were now closely focused on the generating data. They were constantly analysing patterns generated by the digital dataloggers, linking the results back to their hypothesis and predictions, sharing possible mechanisms, anticipating results, and discussing anomalies. Students also demonstrated an awareness of the importance of having more trials, fair testing, and consistent results for each trial, engaging with ideas around data quality and validity.

Their conceptual ideas were gradually refined throughout the trials via collaborative dialogue as they transformed the data across multimodal representations. As they translated the generated visual data into their respective data tables, they were presenting mechanisms based on the results, and experienced two shifts in their reasoning processes. The first shift took place during the first foil in the outside trial, when they came to a consensus about the foil reflecting the heat. The second shift took place as they were deliberating on their hypothesis during the second control trial, stating that foil inside acted like an insulator. Though their ideas were only expressed through dialogue, their final summary of the data indicated a more coherent narrative connecting their results with the underlying mechanisms. Compared with the planning stage, students’ reasoning processes gradually shifted toward more formal accounts of the results supported through more fixed representations to analyse and synthesise their data, with a stronger interplay between the construction of representations and the justification of their ideas.
The datalogger: The role of dynamic representational tools

The datalogger was integral to supporting students’ engagement in this inquiry, through the affordances of providing immediate feedback prompting joint discussion as the temperature patterns unfolded, relating students’ physical observations directly to more abstract representations (Rogers, 2008; Rogers & Wild, 1996) and reducing cognitive load (Ainsworth, 2006). The digital device also assisted students in completing this complex experiment within the time-constraints (Hollan et al., 2000).

During their post-investigation VSRI, the case group reflected on how dataloggers supported their inquiry. The students indicated that the dataloggers assisted their experiment in a number of ways. They commented on the visual nature of the data generated and the ongoing data collection that presented accurate and real-time patterns in the data. They also commented that they were freed up from having to constantly collect the data and did not have to wait for the results. Megan stated that she was not sure how else they could have collected the data.

The automated transfer between the repetitive task of data collection and the time-consuming task of graph generation provided instantaneous feedback enabling students to focus on other aspects of the task, such as dialogue around the broad patterns of the results (Ainsworth, 2006; Hutchins, 1995; Valanides & Angeli, 2008). As they were watching the graph generating, they engaged in collaborative dialogue throughout, discussing their observations, interpreting their results, comparing the results with their hypothesis, elaborating on possible scientific explanations, and deliberating on anomalies. They were also having conversations about how to calculate average temperatures, negotiating the
number of trials, and working within the time-constraints. The datalogger supported more time for meaningful interactions with the data than would have been possible with the mechanical processes of translating temperature readings into graphical forms (Rogers, 2008; Rogers & Wild, 1996).

The generation of graphs provided visual patterns and trends in context, with different affordances from numerical or textual data (Rogers, 2008). The visual output enabled students to identify trends, changes, and compare results across trials. The connection of the physical temperature data with their more visual and abstract representation (i.e., graph) directly related the referent (i.e., the temporal variation in temperature) with the representation, supporting direct interpretation as the students constructed meaning during the investigation (Ainsworth, 2006; Rogers, 2008). This addresses one of the main criticisms around practical investigations: students’ inability to connect their observations with scientific ideas or representations (Abrahams & Millar, 2008). This was particularly apparent with the second foil on this inside trial where the datalogger graph showed initial decreasing temperature and the students began deliberating on possible causes.

From a DCog perspective, technologies function as more than just mediators for learning, they become part of the learning, in both a cognitive and practical sense (Hutchins, 1995). As an integral part of the experiment stage, the dataloggers supported students to construct and refine their conceptual understanding of phenomena across multimodal representational forms (Rogers, 2008).

In terms of the practical aspects of learning to use a new technology, the case group demonstrated both a willingness, and by the end of the first control
trial, a proficiency in using multiple digital technologies (e.g., datalogger, laptop, iPhone camera), manipulating the scientific apparatus (e.g., lamp, houses), and coordinating other non-digital elements (e.g., project books), evidence of their effective group collaboration across this distributed system. They were able to integrate all of the elements into a cohesive and productive investigation. The case groups experience with the datalogger was reflective of the whole class, as indicated in the Questionnaire (see Appendix A Q12). Students indicated they had not used it prior to this unit, and most found it challenging to learn how to use. Yet they noted it provided accurate results, generated graphs, and showed the temperature change. One student commented: The benefits of using the dataloggers were that it gave you exact results and put it into a graph to compare to the other materials”.

6.4 Students’ Engagement with the Task: Writing the Report

In the third and final lesson for this project, students assembled in their groups to draft their final report together. During this 75-minute lesson, the students worked in their groups as the teacher circulated around the classroom, assisting when needed. The case group sat side by side, with each student working from her own laptop, with their projects books and SH handouts. They accessed different sections of their Google Docs report simultaneously, clarifying their understanding and crafting their responses. After about 45 minutes, I visited the group to conduct a VSRI. By the end of this lesson, all groups made progress on their respective reports; by the end of the unit, each of the seven groups submitted their reports by the due date.

The case group focused on different parts of their report: addressing the aim, introduction, hypothesis, and data table. Their dialogue centred around
clarifying and critiquing each of these sections, characterised by periods of silences interspersed with comments and questions. The teacher, Sophia walked past a few times and offered advice on how to structure the data table. At one point, while everyone was working on their report, Clara decided to explain how they were working in Google Docs and re-adjusted the camera to focus on a real-time demonstration.

Google Docs: The role of digital collaboration tools

I begin with Clara’s explanation as a way to describe how they were using Google Docs, and how this digital technology supported them to work together. As she was explaining how they do a concurrent edit, the group commented that the technology enabled them “to work as a group effectively” and “collaboratively”. Clara continued her demonstration focusing on the data table while Ina and Megan continued to work on the document. Clara’s demonstration prompted dialogue about their report (Episode 14).

1 Ina: I don’t know, where should I put the average, at the bottom [typing in the average]?

2 Clara: Yeah. Just put the average at the bottom. So, here’s Ina um, editing the data. As you can see here [pointing the camera at Ina]… This is…Can you do the aim, Megan?

3 Megan: Yeah. I [have] already done the aim. Oh, it’s not finished, is it?

4 Clara: This is our start [scrolling up to their title page]…So you can see here – no wasn’t it 300 seconds? 300 seconds isn’t…

5 Megan: It was 180!

6 Clara: OK, good.

7 Ina: It was three minutes.
8 **Clara:** Oh, OK, good.

9 **Megan:** That’s what we’re going with, that’s what I think it is.

10 **Ina:** Yeah we need to change the method. We need to change up the whole method. Because I had it for five minutes and we had it for three tests.

11 **Clara:** Yeah, because things didn’t turn out...

12 **Ina:** It took a bit longer!

13 **Clara:** Yeah it was a shorter period so we didn’t get to do as much of the…the um trials as we would hoped to do.

14 **Ina:** But it’s ok. The data supports our hypothesis.

15 **Clara:** Yeah. So, the data supports our hypothesis. So that’s very good. And…. So we can use that in our end results, like the conclusion and the results.

Clara’s Google Docs demonstration resulted in a cumulative conversation around the temperature differences, where the case group still needed to clarify information around the number of trials, calculate the averages, and decide how to re-represent this information into a data table. Ina also noticed they needed to adjust the time for each trial as well as the number of trials (lines 7,10). Despite not being able to conduct more trials in their investigation, they re-iterated that their data supported their hypothesis (lines 14, 15). While Megan was updating the data table, she began a discussion about the difference between the starting and finishing temperature in their trials (Episode 15).

1 **Megan:** Do you think we should just do…I think we should either just do the starting temperature or the end temperature or the difference. Either one.
2 Ina: No, because we need both. It’s not really about the starting
temperature to the end temperature. It’s about the difference. In between.
So, I don’t know if you should take that out. Or, make another table, make
another table, or something, underneath.

During the experiment, the case group had conversations about how to
record the temperature. During the first foil on the inside trial, while they were
discussing how to organise their data table, Clara mentioned the focus would be
on how much the temperature went up by (see Experiment Episode 8). A few
minutes later, during the second control trial, Megan shared a sudden epiphany
that the focus needed to be on how much the temperature has risen (see
Experiment Episode 10). Despite these earlier conversations, Megan had
difficulties in representing this information in a table. Ina suggested possible
approaches.

At this point during the lesson, I joined the case group for a VSRI,
focusing on episodes from the planning and investigation lessons. During this
interview, I also asked them to reflect on their experience using Google Docs.
The case group explained that they began using Google Docs at the beginning of the school year (i.e., just three months prior). They emphasised how it enabled them to work together on the same document at the same time or at different times and highlighted the features they used: to edit each other’s work for spelling and grammar, identify each other’s contribution through the different font colour, and to use the chat window to make comments that group members can read later on. The case group also mentioned that Google Docs also enabled them to work on the same document separately from three different locations.

Google Docs prompted conversations that helped students clarify their ideas, refine their representations (e.g., data table), and work across space and time. Compared to traditional laboratory reports which are completed by each student separately, Google Docs enabled them to continue working together beyond the class time allocated for the planning and experimental stages. Throughout the report writing, the case group was still engaged in mostly cumulative dialogue to clarify their ideas, refine their writing, and construct their data table. Google Docs enabled students to access, draft, and edit the same document simultaneously. When students were sitting together in the same room, they shared their ideas aloud. When students were working from their respective homes, they said they shared their ideas through online collaboration tools (e.g., chat). According to the Questionnaire, most of the class used Google Docs for their final report (see Q5). Their comments were consistent with the case group, indicating that Google Docs enabled them to work collaboratively, in addition to providing lab report template.
Reflections on students’ learning

The case group’s conceptual learning journey progressed from the planning stage to drafting the report, as they engaged in collaborative dialogue through different representations (e.g., gestures, cartons) using different resources (e.g., datalogger, Google Docs). Their initial tentative and sometimes inconsistent ideas were eventually presented as a more resolved and consistent understanding of their results.

6.4.1 The report

The case group co-constructed their final report, writing their Introduction, Aim, and Hypothesis, as follows:

Introduction: A sustainable house uses specific passive design strategies so it can save energy, water, and money while being comfortable for its occupants. The objective of this task is to investigate a passive design strategy that could be used to create a sustainable house. We chose to investigate the two questions: “Does foil inside a wall help keep a room cool in summer?”; and, “Is foil inside a wall just as effective as having foil on the outside of the wall?” The data used to evaluate these questions will be taken from three model houses, one with foil on the outside, one with foil on the inside, and one with no foil.

Aim: To investigate if foil inside a wall would keep a house cool in summer, and if the foil is placed on the inside, is it just as effective as it being placed on the outside.

Hypothesis: We predict that foil on the outside of a house will keep a house cooler than having it on the inside. This is because having foil on
the outside will reflect heat off the house, and foil on the inside will trap
the heat inside, acting as an insulator.

The case group related their investigation to passive design strategies for sustainable houses, following their teacher’s advice during the project introduction. Their aim combined their two inquiry questions, and their hypothesis included the underlying mechanisms of reflection and insulation. Compared to their tentative beginning during the planning stage and the confusion over their hypothesis during the initial trials, they presented their ideas coherently and consistent with scientific ideas. For their conclusion, they wrote:

In conclusion, having foil on the inside of a box isn’t effective at keeping a house cool in the summer, because in only three minutes the temperature inside a box with foil on the inside rose on average by 1.45°C. In the cardboard box with foil on the outside, the temperature decreased by 1.6°C on average, proving that a house with foil on the outside will be kept cool in summer.

In a VSRI, I asked the case group to reflect on their results (Episode 16).

1 Clara: It was kinda opposite to what we originally thought.

2 Ina: But once we sort of…once Megan told us, and then once we thought about it more, it matched our hypothesis.

3 Connie: Megan, anything to add to that?

4 Megan: It was kinda what I expected to happen. I wasn’t exactly sure how the foil on the inside was going to work. I wasn’t sure if it was going to work like an insulator on the inside because I thought it might conduct more heat. But I wasn’t sure about the foil on the inside.
5 Ina: That’s the one we were more sure about. Like I thought that foil on the inside would heat up, but I wasn’t so sure about foil on the outside.

Their reflections confirmed the tentative nature of their initial ideas during the planning stage, as well as during the experiment where students were constantly comparing the results with their hypothesis and sharing ideas about plausible mechanisms. I also asked them to reflect on their experiment design. They indicated they would have wanted more time to do three trials and allow the probe to cool down between trials. The Evaluation section of their final report elaborated on their reflections:

The method was effective, however further consideration should have been put into how much time was allowed, and what could be completed in that time. Originally the method planned for three trials, but the group could only do two in the time to complete that prac. Also, more time should have been left for the cardboard boxes to cool, so accurate and consistent results could have been collected. Both the cooling time and extra trials could have contributed to better and more reliable results.

The evaluation was consistent with Megan’s comments about allowing the houses to cool down between trial (see Episode 10), suggestive of students’ awareness of fair testing and reliability in scientific investigations. Overall, the case group’s report provided evidence of a clearly reported investigation, linking their hypothesis to their method, identifying their variables, and relating their results to their conclusion. The case group was also able to relate their investigation to sustainable house designs and energy saving, linking their learning to the broader socio-scientific context. The task did not require students to visually represent the mechanisms for heat transfer, a missed opportunity for
students to map their ideas for a stronger conceptual link to the underlying mechanisms. Applying the RCA reasoning framework, the case group indicated more formal reasoning processes to justify and present their claims through their co-constructed written report. Google Docs enabled the collaborative clarification and refinement of ideas into the written format.

6.5 Chapter Summary

This summary addresses the nature of the task, the nature of the learning within each of the subtasks in relation to the representational resources and practices, and the patterns elicited through the DCog analysis that indicated a more authentic scientific inquiry experience. The task provided a guided induction into epistemic processes of scientific investigations. Students were required to design and undertake an investigation based on their choice of inquiry question(s) and the resources provided, and to choose a format for their final report. In response, students engaged in cumulative and exploratory dialogue to eventually establish a consensus on their hypothesis and experimental design, reflect on the data as it was being generated, and relate their ideas to their observations, based on evidence (Abrahams & Miller, 2008; Mercer, 2004; Rogers, 2008). Through these guided choices, they applied inquiry approaches to solve relevant problems and participated in the meaning-making process through ongoing generation and refinement of their ideas based on scientific concepts (Tytler & Prain, 2013a; Mercer et al., 2004). To complete the task within the limited time required, students need to distribute and coordinate their collective knowledge and abilities using the resources available in this DLE (Hutchins, 1995; Pea, 1993). Students were provided with guidance, tools, and an expectation to work together. In response, they demonstrated a high degree of
collaborative engagement in the task. Each of the three stages of this task addressed specific goals of the inquiry, enlisted specific representational resources, engaged disciplinary practices, and resulted in specific patterns of students’ collaborative reasoning.

In the planning stage, students engaged in exploratory dialogue around more transient representations, resulting in tentative predictions. Their informal dialogue oriented around transient representations of gestures and manipulative experimentation of scenarios with the physical models. This was accompanied by sometimes contradictory ideas (e.g., foil reflects and absorbs heat) along with tentative predictions written in their project books. During their experiment, students negotiated their claims as the data was generated, and enlisted representations to organise and justify their claims. The real-time data generated by the datalogger prompted collaborative reasoning, pattern interpretation, and synthesis. Students were linking representations spontaneously by organising and re-representing visual data from the datalogger into data tables, demonstrating increased representational competence. Megan’s data table demonstrated further interpretations and re-representation of the raw data (see Figure 6.8), a result attributed to the affordances of the datalogger. Over the two series of trials, students’ dialogue showed a gradual refinement of their ideas in response to the data. Their summary statement of the results also demonstrated a high level of representational competence and engagement with the interpretive and communicative practices of scientific inquiry. The formal task of report writing was enacted as group-activity and supported through a digital collaboration tool. This enabled students to refine and resolve their ideas in both verbal and written form through flexible synchronous and asynchronous communication, translating
across modes, space, and time, demonstrating key affordances for online learning processes (Longo, 2016; Valanides & Angeli, 2008). Their conceptual ideas were clearly and comprehensively expressed in their report, demonstrating of their resolved conceptual understanding expressed through formal reasoning processes. Despite missing formal instruction in radiation, the greenhouse effects and light (i.e., Activities 8.4, 8.5, and Module 9), students’ final explanation of reflection as a causal mechanism was consistent. An additional activity requiring students to visually represent the mechanisms for heat transfer would have provided an additional mode by which students could translate their conceptual understanding.

Using the DCog framework to relate students’ learning to the task, tools, and practices resulted in two major patterns. Firstly, students’ initial informal and tentative meaning-making processes were associated with non-digital and transient representations along with more exploratory dialogue. Secondly, as students enlisted more representational resources, including those of a digital nature, they re-represented and refined their ideas as they continued to engage in collaborative dialogue, eventually resolving their ideas in a written report. These patterns suggested a coupling between the resources and actions of the students, consistent with an effective DCog system (Zhang & Patel, 2006) and ideas about developing cognition (as understood through actions) in relation to cultural practices (Tenenberg & Knobelsdorf, 2014). These ideas are consistent with socio-cultural theories that underpin RCA (see Tytler & Prain, 2012).

An in-depth look at students’ responses to the summative task showed that students’ dialogue and interactions were distributed across digital and non-digital tools as they constructed meaning, undertook their experiment, re-represented,
and refined their ideas. As the final summative task of the unit, students were challenged to apply their conceptual knowledge and engage directly in epistemic processes as a collaborative undertaking. The case group engaged in cumulative and exploratory dialogue throughout the investigation, built around key representational resources such as gestures, models, dataloggers, and Google Docs. They applied their conceptual knowledge of energy transfer (e.g., reflection, insulation) as plausible explanations, and revised and refined their ideas over the three lessons during this guided-inquiry. By the end of their experiment, they had shifted their ideas about foil on the outside absorbing heat, and in their final report, they were able to attribute the correct scientific processes of energy transfer, indicating a learning gain, and more importantly, experiencing the active knowledge-building practices of scientific inquiry. The role for both formal, informal, and sometimes inconsistent reasoning processes in scientific inquiry are addressed in the Discussion Chapter.
Chapter 7. Students’ Learning

The purpose of Chapter 7 is to present students’ overall learning journey in this unit. It addresses the RQ 3: *What were the patterns of conceptual and representational development in response to this RCA in this digital environment?* I argue that students showed improved, though inconsistent conceptual understanding and representational competence. Their patterns of conceptual and representational development related to their experiences of the representational resources in the learning sequences to support meaning-making processes.

To understand students’ learning pathways, I begin with an analysis of their pre- and post-test responses to identify the broader patterns of learning gains and challenges, then link these to students’ experiences with the representational sequences across the unit. The analysis is organised into three sections. In the first section, I perform class- and case-level analyses of students’ pre- and post-test responses. In the second section, I present the process and application of my assessment of the case group’s open-ended responses to identify conceptual gains and challenges. These results focus my analysis of the case group’s learning pathways across Modules 2–8, linking their learning to classroom processes as a distributed cognitive system. In the third section, I assess the case group’s learning gains from the summative inquiry task in the context of the overall unit. To begin, I highlight the key concepts of the unit and compare students’ responses to the pre- and post-tests.
7.1 Pre- and Post-Test: What I know about Energy – What I now know about Energy

The online pre- and post-tests surveyed students’ knowledge of energy, energy transfer, climate change, convection, conduction, and radiation. Students completed this test individually. The questions were based on the key scientific concepts and common alternative conceptions related to the above topics, allowing students to express their understanding through multiple choice questions (MCQs) and drawings. The key concepts were characterised in the unit as follows:

Temperature: The temperature of an object is related to the average kinetic energy of the particles that make up the object. There is an absolute zero temperature (0 degrees Kelvin) at which particles have no energy – at any other temperature, the particles must be moving. The greater the temperature, the greater the kinetic energy of the particles.

Thermal Energy: The thermal energy of an object relates to the total kinetic energy (i.e., movement) of the particles that make up the object. Heat is the amount of thermal energy that gets transferred from hot objects to cooler objects.

Particle Model: Scientists use particle ideas to explain what they observe about matter. Particles exist in all matter and are connected, have kinetic energy/thermal energy associated with movement.

Energy Transfer: Energy can be transferred by conduction, convection or radiation, depending on the nature of the material (i.e., solid, liquid, gas). Conduction is the transfer of kinetic energy through the collision of
particles in physical contact. Convection is the transfer of energy between an object and its environment, due to fluid motion in a liquid or gas. Energy transfer involves the bulk movement of particles between hot and cooler objects.

Radiation is the transfer of energy from the movement of charged particles within an atom converted to electromagnetic radiation which can travel through space. Energy transfer does not take place via particles.

The Greenhouse Effect: The most common greenhouse gases are carbon dioxide, nitrous oxide, and methane. In the atmosphere, they absorb and trap heat re-radiated from the Earth and have maintained an average Earth temperature for thousands of years, sustaining life as we know it.

Of the 15 pre- and post-test items, 10 questions related to the unit *as experienced* (vs. the unit *as planned*). Of these 10 questions, I analysed the seven MCQs using descriptive and inferential statistics, and the three open-ended questions using two assessment frameworks, which are explained later in this section.

*7.1.1 Statistical analysis of the multiple choice questions*

*Descriptive statistics*

Of the 27 students, 26 students completed both the pre- and post-tests. The average score for these 26 students was 43% and 53% respectively. In the case group, Ina and Megan performed below the class average in the pre-test, and Ina’s result was above the class average in the post-test. Clara performed above the class average in both. Megan and Ina showed the greatest learning gains. Table 7.1 presents the pre- and post-test results for the class and the case group.
Table 7.1

Pre- and Post-Test Results

<table>
<thead>
<tr>
<th></th>
<th>Pre-test</th>
<th>Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class Average</td>
<td>43%</td>
<td>53%</td>
</tr>
<tr>
<td>The Case Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ina</td>
<td>29%</td>
<td>57%</td>
</tr>
<tr>
<td>Megan</td>
<td>14%</td>
<td>43%</td>
</tr>
<tr>
<td>Clara</td>
<td>57%</td>
<td>57%</td>
</tr>
</tbody>
</table>

**Inferential statistics**

To determine if there were significant differences in the means between the pre- and post-tests, I used SPSS (Version 23) for inferential analyses. I first applied the Shapiro-Wilk test to test for normality: the test showed the pre-test results were normally distributed but the post-test results were not. As the data was non-parametric, I then I applied the Wilcoxon Signed Rank Test to test the null hypothesis: that there is no difference in the mean ranking of the pre- and post-test scores for the paired test scores of each participant (N = 26). The Wilcoxon Signed Rank Test showed a statistically significant difference in pre- and post-test scores (Z = 174.500, p = 0.009). There were positive differences for 16 students, negative differences for four students, and six ties. Thus, I rejected the null hypothesis and assumed that over the entire unit, students developed an improved understanding of the key concepts. Although this inferential analysis showed learning gains, these gains were limited. A case-level analysis enabled me to better understand the extent and patterns associated with their responses in relation to students’ overall learning journey. I begin with an item-level comparison for each of the seven MCQs and answers, comparing the class responses to those in the case group.
7.1.2 An item-level comparison of students’ conceptual understanding

To assess the learning gains for the MCQ I developed a framework of criteria to describe the patterns of conceptual understanding (see Table 7.2).

Table 7.2

Simplified Criteria to Assess Learning Gains in Multiple Choice Questions

<table>
<thead>
<tr>
<th>Criteria for Conceptual Understanding in MCQs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consistent</td>
<td>If the student showed correct responses in both the pre- and post-test.</td>
</tr>
<tr>
<td>Improved conceptual understanding</td>
<td>If the student responded incorrectly in the pre-test and correctly in the post-test.</td>
</tr>
<tr>
<td>Inconsistent conceptual understanding</td>
<td>If the student responded correctly in the pre-test, but not the post-test.</td>
</tr>
<tr>
<td>Persistent alternative conception(s)</td>
<td>If the student responded incorrectly in both pre- and post-tests.</td>
</tr>
</tbody>
</table>

Table 7.3 presents all seven MCQs, their conceptual focus, the possible answers with the correct answer in bold, and the class- and case-level responses.
### Table 7.3

Multiple Choice Questions, Concepts, and Students’ Responses with Correct Answers in Boldface

<table>
<thead>
<tr>
<th>Question</th>
<th>Students’ Responses</th>
<th>Pre-test</th>
<th>Post-test</th>
<th>Conceptual Understanding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Which of the following has thermal energy? (Thermal Energy, Energy Transfer and Transformation)</strong></td>
<td>Class-level response</td>
<td>19%</td>
<td>63%</td>
<td>Improved</td>
</tr>
<tr>
<td>A. A piece of metal that feels cold but not a piece of metal that feels hot.</td>
<td>Case-level response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. A piece of metal that feels hot but not a piece of metal that feels cold.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. <strong>Both a piece of metal that feels hot and a piece of metal that feels cold.</strong></td>
<td>Ina</td>
<td>B</td>
<td>C</td>
<td>Improved</td>
</tr>
<tr>
<td>D. Neither a piece of metal that feels hot nor a piece of metal that feels cold.</td>
<td>Megan</td>
<td>E</td>
<td>C</td>
<td>Improved</td>
</tr>
<tr>
<td>E. I don’t understand the question or I am not sure.</td>
<td>Clara</td>
<td>A</td>
<td>C</td>
<td>Improved</td>
</tr>
<tr>
<td><strong>2. A student is holding a cold piece of metal in her hand. While she is holding the piece of metal, her hand gets colder. Does the piece of metal get warmer? Why or why not? (Energy Transfer, Conduction)</strong></td>
<td>Class-level response</td>
<td>68%</td>
<td>58%</td>
<td>Inconsistent</td>
</tr>
<tr>
<td>A. Yes, the piece of metal will get warmer because some thermal energy is transferred from the student’s hand to the metal.</td>
<td>Case-level response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. No, the piece of metal will stay at the same temperature because thermal energy is not transferred between the student’s hand and the metal.</td>
<td>Ina</td>
<td>A</td>
<td>A</td>
<td>Consistent</td>
</tr>
<tr>
<td>C. No, the piece of metal will stay at the same temperature because an equal amount of thermal energy is exchanged between the student’s hand and the metal.</td>
<td>Megan</td>
<td>C</td>
<td>B</td>
<td>Persistent</td>
</tr>
<tr>
<td>D. Yes, the piece of metal will get warmer because some thermal energy is transferred from the metal to the student’s hand.</td>
<td>Clara</td>
<td>C</td>
<td>A</td>
<td>Improved</td>
</tr>
<tr>
<td>E. I don’t understand the question or I am not sure.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. A student places a warm can of soda into a bucket filled with cold water. She puts the lid on the bucket. Which of the following describes the energy transfer between the water and the can of soda in the bucket? (Energy Transfer, Convection)
   A. Thermal energy is transferred from the can of soda to the water so the can of soda gets cooler and the water stays the same temperature.
   B. Thermal energy is transferred from the can of soda to the water so the can of soda gets cooler and the water gets warmer.
   C. Coldness is transferred from the water to the can of soda so the can of soda gets cooler and the water stays the same temperature.
   D. Coldness is transferred from the water to the can of soda so the can of soda gets cooler and the water ice gets warmer.
   E. I don’t understand the question or I am not sure.

<table>
<thead>
<tr>
<th>Class-level response</th>
<th>26%</th>
<th>46%</th>
<th>Improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-level response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ina</td>
<td>C</td>
<td>A</td>
<td>Persistent</td>
</tr>
<tr>
<td>Megan</td>
<td>D</td>
<td>A</td>
<td>Persistent</td>
</tr>
<tr>
<td>Clara</td>
<td>C</td>
<td>A</td>
<td>Persistent</td>
</tr>
</tbody>
</table>

4. Consider a light bulb and an ice cream cone. Which gives off energy by radiation and why? (Energy Transfer, Radiation)
   A. Both a light bulb and an ice cream cone because all objects radiate energy.
   B. Neither a light bulb nor an ice cream cone because only the sun radiates energy.
   C. Only a light bulb when it is glowing because only glowing objects radiate energy.
   D. Only a light bulb when it is hot because only hot objects radiate energy.
   E. I don’t understand the question or I am not sure.

<table>
<thead>
<tr>
<th>Class-level response</th>
<th>27%</th>
<th>58%</th>
<th>Improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-level response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ina</td>
<td>A</td>
<td>A</td>
<td>Consistent</td>
</tr>
<tr>
<td>Megan</td>
<td>A</td>
<td>A</td>
<td>Consistent</td>
</tr>
<tr>
<td>Clara</td>
<td>A</td>
<td>A</td>
<td>Consistent</td>
</tr>
</tbody>
</table>

5. Consider the following situations: Situation 1: A cold spoon is placed in a cup of hot tea. Situation 2: An ice cube is placed in a cup of hot tea...Is energy being transferred in either of these situations? (Energy Transfer and Transformation; conduction in a solid, convection in a liquid)
   A. Energy is NOT transferred in either situation.
   B. Energy is transferred when an ice cube is placed in a cup of hot tea, but energy is NOT transferred when a cold spoon is placed in a cup of hot tea.
   C. Energy is transferred when a cold spoon is placed in a cup of hot tea, but energy is NOT transferred when an ice cube is placed in a cup of hot tea.
   D. Energy is transferred in both situations.
   E. I don’t understand the question or I am not sure.

<table>
<thead>
<tr>
<th>Class-level response</th>
<th>48%</th>
<th>58%</th>
<th>Improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-level response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ina</td>
<td>B</td>
<td>D</td>
<td>Improved</td>
</tr>
<tr>
<td>Megan</td>
<td>C</td>
<td>D</td>
<td>Improved</td>
</tr>
<tr>
<td>Clara</td>
<td>D</td>
<td>D</td>
<td>Consistent</td>
</tr>
</tbody>
</table>
A girl is sitting under an umbrella at the beach on a sunny day. When she moves out of the shade and into the sunlight, she will feel warmer. Why? (Energy Transfer and Transformation, Radiation, Reflection)

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>Because energy is being transferred directly from the sun to the girl.</td>
</tr>
<tr>
<td>B.</td>
<td>Because energy is being transferred from the sun to the air and then from the air to the girl, but no energy is being transferred directly from the sun to the girl.</td>
</tr>
<tr>
<td>C.</td>
<td>Because energy is being transferred from the sun to the ground and then from the ground to the girl, but no energy is being transferred directly from the sun to the girl.</td>
</tr>
<tr>
<td>D.</td>
<td>Because the sun is shining on the girl, not because energy was transferred from the sun to the girl.</td>
</tr>
<tr>
<td>E.</td>
<td>I don’t understand the question or I am not sure.</td>
</tr>
</tbody>
</table>

The natural greenhouse effect is caused mainly by the: (Energy Transfer, Radiation; re-radiation of infrared light/heat)

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>Direct trapping of solar radiation as it moves down through the atmosphere.</td>
</tr>
<tr>
<td>B.</td>
<td>Trapping by the atmosphere of radiation re-emitted by the earth’s surface.</td>
</tr>
<tr>
<td>C.</td>
<td>Inability of solar radiation to penetrate the atmosphere.</td>
</tr>
<tr>
<td>D.</td>
<td>Increase in greenhouse gases due to human activity.</td>
</tr>
<tr>
<td>E.</td>
<td>I don't understand the question or I am not sure.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class-level response</th>
<th>48%</th>
<th>56%</th>
<th>Improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-level response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ina</td>
<td>B</td>
<td>B</td>
<td>Persistent</td>
</tr>
<tr>
<td>Megan</td>
<td>C</td>
<td>A</td>
<td>Improved</td>
</tr>
<tr>
<td>Clara</td>
<td>A</td>
<td>A</td>
<td>Consistent</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class-level response</th>
<th>15%</th>
<th>40%</th>
<th>Improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-level response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ina</td>
<td>D</td>
<td>D</td>
<td>Persistent</td>
</tr>
<tr>
<td>Megan</td>
<td>A</td>
<td>A</td>
<td>Persistent</td>
</tr>
<tr>
<td>Clara</td>
<td>B</td>
<td>D</td>
<td>Inconsistent</td>
</tr>
</tbody>
</table>
7.1.3 Summary of students’ learning at a class- and case-level

Though there were overall learning gains for the class as a whole, the results suggested that there was variation in students’ prior knowledge for the test items compared to the literature, with limited gains. The first six test items were based on those from the AAAS (2018) website with the addition of option “E”, where students could choose “I don’t understand the question or am not sure”. Because the items were not exactly the same as those presented in the literature, I provide a descriptive comparison of the class-level responses based on the same concepts and similar aged groups (i.e., Years/Grades 9-12). For Q1, Q3, and Q5, the class responses in the pre-test were lower than similar results in the literature (i.e., 48%, 46%, and 66% respectively), suggesting that this class had challenges with understanding the nature of heat transfer (vs. coldness transferring) (AAAS, 2018). Students’ responses to Q7 suggested challenges in understanding the natural greenhouse effect, similar to results in other studies (Besson & De Ambrosis, 2014; Dawson, 2015). Students’ responses to questions 2, 4 and 6 were similar to that of the literature, though Q2 was the only item not linked to a class-level improvement, suggesting persistent alternative conceptions for this class.

At a case-level, Ina and Megan showed the greatest learning gains in the pre- and post-tests; though Clara’s pre- and post-test results were the same, her item-level responses were different. As a group, they had consistent responses for energy transfer and radiation (Q4), contrary to the class-level trends. They had persistent alternative conceptions for energy transfer and convection (Q3), consistent with the class-level trends though their responses indicated they no longer attributed the change to coldness transferring. They also had improved understanding for energy transfer (Q1), each with their own unique prior ideas.
For the remaining MCQs, their responses were idiosyncratic. Their open-ended responses provided additional insight into their conceptual understanding along with their ability to generate representations.

7.1.4 Assessing the open-ended responses

The three open-ended questions allowed students to more flexibly express their ideas using the interactive canvas. Question 8 related to energy transfer and conduction: “How does the heat in an iron rod warm the hand?” Question 9 related to energy transfer through convection: “How does a wool glove keep your hand warm if you are holding a snowball?” Question 10 related to radiation: “What is the Greenhouse effect?” The diagrams provided for Q8 and Q9 are included in Ina’s responses (see Figures 7.1 and 7.2). All students in the class responded using text, diagrams, or a combination of the two.

In this unit, students’ conceptual understanding was assessed primarily through closed-ended MCQs; students’ SGRs were intended to be assessed through teacher-led discussions focusing on aspects such as purpose and adequacy. Addressing the pre- and post-tests SGRs presented challenges in assessing students conceptual understanding and representational competence (RC), an issue which has been addressed in other studies.

Hilton and Nichols (2011) investigated Year 11 chemistry students’ development of conceptual understanding and representational competence in response to a representation-focused unit. Their pre- and post-test also consisted of a combination of closed-ended MCQs and open-ended responses. To assess the open-ended responses, they devised a modified version of Kozma and Russell’s (2005) Levels of Representational Competence to suit a high school audience. They applied this framework to assess both textual and visual modes of students’
responses. Michalchik et al. (2008) used the same approach in their open-ended pre- and post-test items: applying Kozma and Russell’s (2005) framework to determine students’ overall RC instead of the correctness of the responses. They also developed a conceptual-criteria rubric to assess specific aspects of students’ responses regarding molecular bonding structures.

For my investigation, the three open-ended questions allowed for students to choose the mode of representations in their response, as the interactive canvas accommodated both textual and visual modes (e.g., written text, drawing, symbols). I used two different frameworks: one to assess students’ conceptual understanding and another to assess their representational competence. Following a similar approach to Michalchik et al. (2008), I developed conceptually-based criteria for each of the three questions based on the content in STILE (see Table 7.4). Similar to the process I used to assess SGRs in Chapter 5, students’ conceptual understanding was assessed based on the consistency of their responses to scientific information presented in STILE. To assess their level of RC, I followed a similar approach to Hilton and Nichols (2011) by modifying Kozma and Russell’s (2005) rubric to suit secondary students (see Table 7.5).

Assessing students’ conceptual understanding

To assess students’ conceptual understanding for the three open-ended questions, I constructed key aspects to explain each of the phenomena based on scientific explanations provided in the unit (see Table 7.4).
Table 7.4

Structure of Scientific Explanations used as Criteria for Scoring each of the three Open-ended Questions.

<table>
<thead>
<tr>
<th>Question 8: How does the heat in an iron rod warm the hand?</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Heat is transferred from a warmer object to a cooler object (i.e., from the end of the rod closest to the flame, towards the hand).</td>
</tr>
<tr>
<td>• The particles closer to the flame gain kinetic energy, which is transferred through collisions toward the particles at the cooler end of the rod.</td>
</tr>
<tr>
<td>• Energy transfer through solid particles is called conduction.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question 9: How does a wool glove keep your hand warm if you are holding a snowball?</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Heat is transferred from a warmer object to a cooler object (i.e., from the hand to the snowball).</td>
</tr>
<tr>
<td>• The wool acts as an insulator, with pockets of air that slow the rate of particle collisions and energy transfer.</td>
</tr>
<tr>
<td>• Energy transfer through fluid (e.g., air) particles is called convection.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question 10: What is the greenhouse effect?</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Light energy from the sun is absorbed by the Earth. As the Earth warms, some of this energy is re-radiated as heat/infrared energy.</td>
</tr>
<tr>
<td>• Certain gases in the atmosphere (e.g., carbon dioxide, nitrous oxide, methane) trap this heat energy resulting in a natural greenhouse effect.</td>
</tr>
<tr>
<td>• This natural greenhouse effect maintains an average Earth temperature that sustains life.</td>
</tr>
</tbody>
</table>

In scoring students’ responses, each answer could generate up to three points, with responses partially addressing an aspect resulting in ½ point. I provide an explanation of how I scored Ina’s responses in Figures 7.1, 7.2, and 7.3.

Assessing students’ representational competence

Kozma and Russell’s (2005) framework presented strengths and limitations in assessing SGRs. Their design was informed by the practices of scientists, based in situative theory and thus more reflective of the socio-semiotic
and epistemic perspectives underpinning representational pedagogies (Prain & Tytler, 2012). Their framework also focused solely on the written and visual modes (i.e., static representations) (see Mayer, 2001), which reflected students’ test responses. The patterns of development from levels 1–5 were contingent on the types of material and social resources available.

Following Michalchik et al. (2008), I developed a simplified version of the framework suited to the emerging RC of high school students, and reflective of the diverse range of representational resources and tools in this DLE. Table 7.5 presents my simplified RC rubric where levels 1–3 focus more on superficial features (i.e., characteristic of novices), and levels 4–5 have a more relational and reflective use of representations (i.e., characteristic of expert behaviour). Because students could conceivably score well on RC yet retain persistent misconceptions, I applied the frameworks in Tables 7.4 and 7.5 to assess students’ responses.
### Table 7.5
Summary of Levels of Representational Competence

<table>
<thead>
<tr>
<th>Level of RC</th>
<th>Features of Students’ Representation(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LEVEL 1</strong></td>
<td>• Focus on physical or macroscopic features</td>
</tr>
<tr>
<td><em>Depiction</em></td>
<td></td>
</tr>
<tr>
<td><strong>LEVEL 2</strong></td>
<td>• Focus on physical or macroscopic features</td>
</tr>
<tr>
<td><em>Symbolic</em></td>
<td>• Include some symbolic features (e.g., arrows signifying time)</td>
</tr>
<tr>
<td><strong>LEVEL 3</strong></td>
<td>• Include both macroscopic and submicroscopic features or processes</td>
</tr>
<tr>
<td><em>Syntactic</em></td>
<td>• Focus on syntax only (i.e., form of words, phrases, and sentences), instead of meaning</td>
</tr>
<tr>
<td></td>
<td>• Use one or more representations of the same phenomenon linked through shared physical features and syntax</td>
</tr>
<tr>
<td><strong>LEVEL 4</strong></td>
<td>• Include both macroscopic and submicroscopic causal features or processes</td>
</tr>
<tr>
<td><em>Semantic &amp; Relational</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Focus on both syntax and semantics (i.e., meaning of words and symbols)</td>
</tr>
<tr>
<td></td>
<td>• Link or transform meaning across two representations</td>
</tr>
<tr>
<td></td>
<td>• Spontaneous use of representations to explain a phenomenon</td>
</tr>
<tr>
<td><strong>LEVEL 5</strong></td>
<td>• Include both macroscopic and submicroscopic features or processes</td>
</tr>
<tr>
<td><em>Reflective</em></td>
<td>• Focus on both syntax and semantics (i.e., meaning of words and symbols)</td>
</tr>
<tr>
<td></td>
<td>• Use specific features to make claims</td>
</tr>
<tr>
<td></td>
<td>• Express understanding of purpose and critical reflection of representations</td>
</tr>
</tbody>
</table>

As an exemplar, I present a detailed summary of the application of both frameworks to compare my assessment of Ina’s pre- and post-test representations (see Figures 7.1, 7.2, and 7.3), along with the details of how I scored them.

In addition, a week after the post-test, I followed up with interviews where students shared their reflections on their quiz responses. For the other two members of the case group, I provide a summary of their quiz responses in
addition to excerpts from their interviews. The change in the case group’s responses provided information on their conceptual growth and the challenges they encountered. At the end of this section, I address the key issues with the questions.
**Question 8.** If you place one end of an iron rod in a fire and you hold the other end after a while the end you are holding feels warm.

**PRE-TEST**

**POST-TEST**

**RESPONSE TO CRITERIA (see Table 7.4)**

Ina indicated the direction and movement of heat/energy from the flame to the hand. (1 point)

Ina wrote: “The red particles represent the hot end of the rod, and the blue represents the cooler ones. The particles are all touching because the rod is solid, and they are moving which is represented by the arrows. The particles would all be moving around and rubbing against each other, which transfers the heat, if the heat source continued to heat up, eventually the heat would travel all the way to the end where the hand is holding.”

Ina indicated the direction and movement of heat/energy from the flame to the hand (1 point); that the moving particles are in contact and rubbing against each other as the mechanism of transfer (1 point); that energy transfer took place through a solid (1 point). (3 points)

**REPRESENTATIONAL COMPETENCE (see Table 7.5)**

Ina constructed an annotated macroscopic diagram of the flame, bar and hand, similar to the one provided in the question provided. She used symbolic arrows to show the direction of heat transfer. Ina also used a wavy red line symbol to indicate unobservable transfer of heat. (Level 3)

Ina constructed a more abstract diagram compared to the one in her pre-test, including observable processes and non-observable processes (e.g., particles, amount of heat in particles). She used a written explanation in addition to more specific annotations. Ina also related meaning across the two representations. (Level 4)

Figure 7.1. Ina’s pre-test (left) and post-test (right) responses to Q8.
The improvement in Ina’s understanding was shown through both her textual and visual accounts. The text identified features in the diagram and elaborated on the mechanism of transfer, though was missing some key terminology; the diagram showed the submicroscopic features but did not depict any movement. Overall, Ina indicated a pattern toward a more comprehensive understanding of conduction expressed through multiple and multimodal representations in her MCQs and open-ended responses. Upon comparing the pre- and post-test responses during the interview, Ina elaborated on her post-test diagram:

1 Ina: Well, I drew the flame and the rod and the hand as well. And I tried to …and I’m not very good at drawing so I found it easier if I wrote a bit of an explanation as well. But like when we did the demonstration. Like when we did the actual role-play, I was trying to show how the particles are touching each other and then spreading the heat down to the hand. And ‘cause its solid, so they are touching, like buzzing or vibrating against each other. And the arrows sort of show, that its…if the heat is there and it’s hottest down there and slowly moving up towards the hand.

2 Connie: Right. And, what process would describe that movement?

3 Ina: Conduct….ion?

4 Connie: You think its conduction?

5 Ina: I think so, yeah.

During the interview, Ina clarified some of the key concepts in energy transfer and conduction as they related to her diagrams and reflected on the use of representations. She conceded that she was “not very good at drawing” (line 1) so provided the written explanation, indicating RC through spontaneous use of a
representations. To explain the mechanism of energy transfer, she referenced the role-play activity (see Module 6 – Conduction), drawing on specific modal affordances and demonstrating how she was incorporating multiple representations to explain a concept. Ina’s responses to Q9 are presented in Figure 7.2 and examined in more detail below.
Question 9. Garments that are made of wool keep you warm in winter as the material contains pockets of air. Explain how a woolen glove would keep your hand warm if, for example, you picked up a snowball.

PRE-TEST

POST-TEST

RESPONSE TO CRITERIA

Ina wrote: “The wool is keeping pockets of air which are warm from the body heat, and protecting the hand from getting cold, and also using the physical barrier.”

Ina explained that wool is a physical barrier that provides/keeps pockets of air (½ point) and that these pockets are warmed from the body (½ point). (1 point)

Ina wrote: “The Pink on the hand represents the mitten. The mitte (sic) is a solid object, and it is keeping pockets of warm air to keep the hand warm from the snowball. This creates a barrier between the snow and the hand, which is warm because of the warm air pockets.”

Ina explained that mitten provides pockets of air (½ point) which create a barrier. (½ point)

REPRESENTATIONAL COMPETENCE

Ina constructed an annotated macroscopic diagram similar to the one provided in the question. She included a written explanation of the process, but the two representations were not related. (Level 1)

Again, Ina constructed an annotated macroscopic diagram similar to the one provided in the question. She included a written explanation of the process and related the text to the diagram using syntax, though in a superficial manner. (Level 3)

Figure 7.2. Ina’s pre-test (left) and post-test (right) responses to Q9.
For Q9, neither of Ina’s responses indicated an understanding of energy transfer through convection, which reflected her persistent alternative conceptions as expressed in the MCQ (see Q3). During the interview, she elaborated on her ideas:

1 Ina: They [the diagrams] are pretty similar. I think I was sort of thinking the same thing because we done it before [during the pre-test] so I knew the question. I was trying to show...yeah, that diagram wasn’t very helpful. But I’m also showing the mitten. It is solid because it’s wool, it’s probably a bit more spread apart than a metal or a plastic or something like that. And then the air inside is warm. I wasn’t really sure how, but the air inside that’s trapped inside is warm because of the wool, so that’s why it’s not coldness from the snowball isn’t touching your hand.

2 Connie: So where is the heat in this case?

3 Ina: Coming from your hand. It’s the body heat.

4 Connie: And what does the wool glove act as?

5 Ina: I think an insulator.

6 Connie: So if it’s an insulator, what are the particles like in an insulator?

7 Ina: Well I thought that they are probably a bit more spread out. Not like a metal where they are all very close together. Because it’s a wool, it’s a bit more spread out. They would touch, still, but not as compacted.

In the interview, Ina was able to better explain some of the features in this scenario but also expressed confusion. She elaborated on the nature of the woolen material with the particles “more spread apart” (line 1) and “not as compacted” (line 7), and thus acted as an insulator. She also clarified the source of heat as
coming from the hand, warming the air trapped inside the wool, and the wool acting as a barrier. Though her quiz response to the related item in Q5 showed an improved understanding of energy transfer in a solid and liquid, she was not able to account for the mechanism of transfer, other than an explanation of trapped air pockets in the wool fibres. Ina’s response to Q10 is presented in Figure 7.3.

**Question 10.** Scientists make reference to the Greenhouse Effect and its relation to climate change. What is the Greenhouse Effect?

<table>
<thead>
<tr>
<th><strong>RESPONSE TO CRITERIA</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PRE-TEST</strong></td>
<td><strong>POST-TEST</strong></td>
</tr>
<tr>
<td>Ina annotated diagram showed that the greenhouse gas is trapped within some barrier (½ point). (½ point)</td>
<td>Ina wrote: “The sun directs heat towards the earth, and some if it reflects but some of it sits in the layer between the earth (sic). This is where the red represents the CO₂ (sic) and the other gases in the atmosphere which sit here and heat up the earth to an unhealthy amount.” Ina identified the light energy from the Sun, and that some of it is reflected (½). She identified CO₂ as one of the gases (½ point). (1 point)</td>
</tr>
<tr>
<td><strong>REPRESENTATIONAL COMPETENCE</strong></td>
<td></td>
</tr>
<tr>
<td>Ina constructed an annotated macroscopic diagram. She also used the following symbols: a black circle to represent a boundary, wavy blue lines to indicate the area with trapped greenhouse gases, and yellow lines to show sunlight. (Level 2)</td>
<td>Ina constructed a macroscopic diagram that was similar to her pre-test, with the same symbols. In her text, she linked the meaning of the red wavy lines as CO₂, relating the two representations through syntax. (Level 3)</td>
</tr>
</tbody>
</table>
For Q10, Ina’s responses suggested a limited understanding of the greenhouse effect. Her written response in the post-test provided more context for the diagram and an explanation of the process; however, she identified CO₂ and other gases as the causal mechanism for the heating. In her interview, Ina began with her pre-test diagram:

1 **Ina:** I didn’t write anything but I was saying the sun is directing heat towards the Earth. And some of it is reflects... off. But some of it sort of sits between the layer of the Earth and the universe? The atmosphere? I’m not really sure. So like the red is like the carbon dioxide and the other gases sort of surrounding the Earth. Yeah, I think so.

2 **Connie:** So now if we studied conduction, convection, and radiation, what process best describes what’s going on with the greenhouse effect.

3 **Ina:** Conduction, I think...Yeah or it could be insulating...Yeah, I’m not really sure.

4 **Connie:** What would it be insulating?

5 **Ina:** So in that layer, if the sun is the heat source, and the Earth is like a solid, but it’s kind of hard because there is no physical...there’s no physical barrier so it’s sort of all science. Yeah.

In the interview, Ina was better able to explain the mechanism: how the heat was reflected and also how it “sits” (line 1) in that layer. Although she identified a boundary and trapped greenhouse gases in both diagrams, she became confused about the nature of the barrier and did not identify the mechanism of energy transfer through radiation. Her confusion expressed across all three modes was consistent with her incorrect quiz response regarding the greenhouse effect (Q7).
Summary of Ina’s learning

Analysis of Ina’s responses in her pre- and post-tests provided information on her learning gains and the development of her representational competence for an account of her overall growth. Ina’s most significant learning gains were with energy transfer through conduction, showing consistency and improvement in the MCQs and the highest degree of RC. Ina’s weakest learning gains were with energy transfer through convection, showing mixed gains in the MCQs and conceptual understanding in Q9 (though Q9 seemed too complex for the purpose of this assessment and is addressed later in this section). Ina’s showed limited improvement in Q10. In the next section, I relate these patterns to her learning journey across the unit and link them to the classroom processes to gain insight into the impact of the representational sequences. Using the same assessment criteria and process, I analysed Megan and Clara’s responses and provide a summary of their learning.

Summary of Megan’s learning

Compared to Ina, Megan showed similar overall learning gains in the MCQs but more limited improvement with the open-ended responses. Her strongest gains were related to energy transfer in general: that all objects have thermal energy (Q1) and that there is energy transfer when there is a difference in temperature (Q5) (see Table 7.3). However, when energy transfer was specifically related to conduction, she showed persistent alternative conceptions concerning energy transfer through conduction from higher to lower temperatures (Q2 and Q3). Yet, in the iron rod scenario (Q8), Megan was able to depict the direction of energy transfer in pre-test (i.e., from the flame to the hand) and a mechanism through particle ideas in the post-test, though she drew the particles near the heat
closer together and more spread apart as they were further away from the heat, instead of the opposite (see Figure 7.4). In her interview, she explained: “because that’s where the heat is so they are all bumping together more”. Comparing the results of her pre- and post-test, Megan’s conceptual understanding remained at 1 point, although her RC went from Level 2 to 3, as she was able to depict particle ideas, though the spatial arrangement was contradictory (see Table 7.6).

For convection, Megan’s quiz responses were mixed (see Table 7.3). She exhibited a developing understanding of heat transfer in liquids (i.e., melting ice and hot tea) (Q5). However, she had persistent alternative conceptions in the scenario involving a can of warm soda in a bucket of cold water, where she initially indicated coldness transferred, then shifted her thinking to warmer soda cooling with the water temperature remaining the same (Q3).

In the mitten and snowball scenario (Q9), Megan used both text and diagrams, relating the two in the pre-test through syntax, resulting in a Level 3 RC. In her post-test, she wrote: “glove is an insulator, no air can get through”, but did not relate this to her diagram, resulting in a Level 2 RC (see Figure 7.5). Her conceptual understanding remained the same across both tests, at ½ point (see Table 7.6). During the interview, she explained the process of insulation:
“particles would be closer together and that the heat moves slower…through…or faster? I can’t remember”, indicating confusion.

Figure 7.5. Megan’s pre-test (left) and post-test (right) responses to Q9.

For radiation, Megan had a consistent understanding that all objects radiated energy (Q4) and had a developing understanding of how heat was transferred directly from the sun to an object (Q6). However, she had persistent alternative conceptions of the natural greenhouse effect, indicating solar radiation was directly trapped as it moved down through the atmosphere instead of it being re-emitted by the Earth’s surface and trapped by the atmosphere (Q7).

Megan generated annotated diagrams for Q10 (see Figure 7.6). In her pre-test, she wrote: “Warmth is kept inside by the ozone layer, so warmth bounces back to the earth, which makes everything heat up”. Though her conceptual understanding was limited (½ point), she related text to her diagram through syntax, resulting in a Level 3 RC (see Table 7.6). In her post-test response, she wrote: “Sun’s rays get trapped in the earths (sic) atmosphere and cannot escape. This warms the earth (sic)”, indicating that the rays trapped in the atmosphere results in warming, showing an improved but limited understanding (1 point). She provided a similar representation but did not relate the two, resulting in a Level 2 RC.
Her post-test diagram illustrated the ray of sunlight entering the atmosphere and reflecting up to the barrier and remaining, evidence that she was able to express a degree of conceptual understanding through her diagram, but not in the MCQ. Overall, Megan’s post-test responses showed a small improvement in conceptual understanding, limited conceptual gains in her open-ended responses and decreased RC for Q9 and Q10.

**Summary of Clara’s learning**

Clara had the highest pre-test score in her group. For energy transfer, Clara exhibited developing understanding that all objects have thermal energy, including a piece of metal that feels cold (Q1), and that energy transfer took place through a temperature gradient (Q2). She also had a consistent understanding that energy transfer takes place when there is a difference in temperature (Q5) (see Table 7.3).

For the open-ended responses, Clara used the same image provided in Q8 and Q9 (see Figures 7.7 and 7.8). In Q8, she used arrows to show the direction of energy transfer in the iron rod (i.e., from the flame to the hand) (see Figure 7.7). In her pre-test, she wrote: “the thermal energy from the flame will transfer to the rod then slowly move towards the other end”. In her post-test, she explained that
as the particles got warmer, the gained kinetic energy and vibrated more, “causing heat to be transferred to the end of the rod”, consistent with the scientific ideas. Her conceptual understanding improved from 1 point to 1½ points and her RC went from Level 2 to 3 as she was able to depict particle ideas (see Table 7.6).

In the interview, Clara elaborated on the mechanism using particle ideas: “The ones closer to the flame, they have more kinetic energy so they start moving faster. So they bump into these ones and they start to move, so that shows the heat transferring to the other end.”

For convection, Clara had persistent alternative conceptions in understanding the direction of heat transfer when applied to convection currents, first attributing coldness being transferred, then indicating that transfer only takes place in one direction (Q3). Her pre-test response (Q9) included the same diagram provided in the questions in addition to the following text: “the coolness from the snow is not transmitted to your hands because and the small air pockets in the gloves that trap the energy from the snow”, resulting in ½ point (see Figure 7.8).
Figure 7.8. Clara’s pre-test (left) and post-test (right) responses to Q9.

Her post-test explanation showed a shift in her understanding that thermal energy originated from the body in this scenario and was trapped inside the gloves, resulting in 1 point. She wrote: “thermal energy is being produced by the human body and the wool helps to trap the energy inside the gloves so even if you pick up the snow your hands would still be warm”. In her diagram, however, she did not provide a mechanism for this transfer except for an arrow that signified the glove keeping the heat in the hand, resulting in a Level 1 to Level 2 progression. In the interview, she stated conduction “keeps your hands cool or something. But like with insulating, ‘cause this is like insulating your hand, it’s keeping the heat inside the glove”, attempting to connect the two processes in the complex scenario. In describing the role of the insulator, she explained: “your hands have more kinetic energy but the snowball wouldn’t have as much kinetic energy because the heat is more cooler.”

For radiation, Clara showed consistent understanding that all objects radiated energy (Q4) and that heat transferred directly from the sun to an object (Q6). However, she had an inconsistent understanding of the natural greenhouse
effect (Q7), initially indicating that it was due to atmospheric trapping of re-radiation heat then changing to it being attributed to human activity.

In Q10, Clara provided a written explanation in her pre-test: “the greenhouse effect is the process of the sun heating up the surface of the earth. When the sun’s energy touches the atmosphere, the energy is returned back to space but the rest of the energy is absorbed by the greenhouse gases” (see Figure 7.9). She explained that some of the Sun’s energy was reflected but absorbed (instead of being trapped) by the greenhouse gases, resulting in 1½ points. She depicted this in her post-test diagram, showing annotations and symbols, resulting in a Level 2 RC.

![Figure 7.9. Clara’s pre-test (left) and post-test (right) responses to Q10.](image)

In the interview, Clara explained that the yellow lines represented “the energy from the Sun” and that the heat was coming towards the Earth. She also identified the greenhouse gases [pointing to the diagram] and explained they trap “the Sun’s heat so the Earth becomes more hotter.” I asked her why she provided a diagram in the post-test and she said: “Maybe because I understood it more so it was just easier to do a diagram.” Though she was expressing an improved understanding during the interview, her diagram did not include these ideas, resulting in a more limited RC.
Summary of the case group

Combining the case group’s responses to the MC items (see Table 7.3) with the open-ended responses (see Table 7.6), the strongest overall learning gains (i.e., conceptual understanding and representational competence) were associated with energy transfer and conduction, the least were with convection, and there were limited gains with radiation, with instances of decreased scores. These broad patterns indicate the variation in students’ learning journeys and will guide my subsequent analysis of their responses related to the representational sequences across the unit.

Table 7.6
Summary of the Case Group

<table>
<thead>
<tr>
<th>Question 8 - Conduction</th>
<th>Question 9 - Convection</th>
<th>Question 10 - Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-test</td>
<td>Post-test</td>
</tr>
<tr>
<td>Ina</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conceptual Understanding</td>
<td>1 point</td>
<td>3 points</td>
</tr>
<tr>
<td>Representational Competence</td>
<td>Level 3</td>
<td>Level 4</td>
</tr>
<tr>
<td>Megan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conceptual Understanding</td>
<td>1 point</td>
<td>1 point</td>
</tr>
<tr>
<td>Representational Competence</td>
<td>Level 2</td>
<td>Level 3</td>
</tr>
<tr>
<td>Clara</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conceptual Understanding</td>
<td>1 point</td>
<td>½ points</td>
</tr>
<tr>
<td>Representational Competence</td>
<td>Level 2</td>
<td>Level 3</td>
</tr>
</tbody>
</table>
Reflections on the test questions

In analysing students’ responses to the test questions, three key issues emerged which might have influenced their results. The first issue related to the images provided in Q8 and Q9 and their influence on the SGRs. Twenty-six of the pre-test responses to Q8 replicated the image of the heating rod and followed the same colour patterns; only one response was text-based. The iconic image in Q9 also influenced the SGRs. Of the 26 pre-test responses, three students used the same image in their response with additional annotations, 16 generated a similar diagram of a snowball and mitten(s), and 12 used pink, purple, or red for the mittens. Q10 did not provide an image, and students’ responses showed the greatest variety of SGRs, ranging from globes, to schematics, to causal effects (see Figure 7.10). Similarly, the repetition of the iron-rod scenario in the representational-focused EGR-videos might be attributed to the case group’s only consistent learning gain in the open-ended responses (see post-test Q8). These patterns suggest that the provision of EGRs can strongly influence SGRs. If the intention is to focus students’ attention on a specific feature, the provision of diagrams may be useful (see Module 7 convection diagrams). However, it may limit the potential variety of responses. The related issue of timing the introduction of EGRs is addressed in the Discussion Chapter.
The second issue was the complexity of Q9. With Q8 related to conduction, and Q10 related to radiation, Q9 would have ostensibly focused on convection. However, both conduction and convection are plausible explanations for energy transfer in this complex scenario. The task of representing air pockets as a convection cell required more sophisticated conceptual understanding than was presented in the unit to successfully translate these ideas to new contexts and onto a diagram, thus likely influencing the limited results for this test item.

The third issue related to Q10, which focused on the greenhouse effect. Though the case group showed marginal gains in this area, key activities in the radiation module (8.4 and 8.5) were not addressed due to time constraints. Although students would have received general information on the greenhouse effect in Module 3 via an internet-video, they did not engage in the representational activities specifically related to the more complex interactions of reflection, absorption, and re-radiation involved in the greenhouse effect. This would have supported a more comprehensive understanding of the scientific explanation as indicated in Table 7.4.

This section has provided insight into the case group’s learning through their pre- and post-test responses, providing a reference point to track the
complexity of their learning through the modules. The next section reviews the learning journey of the case group, with the representational sequences related to conduction, convection, and radiation.

7.2 Learning Pathways through the Modules: Conceptual and Representational Development

Following the pre-test, students engaged in their respective learning pathways about energy transfer through conduction, convection, and radiation in the context of sustainable housing. I begin with a brief overview of students’ responses in Modules 1–4, which focused on establishing the context for the unit. I then continue with a more comprehensive analysis of the conceptual Modules 5–8 informed by socio-semiotic and distributed cognitive theories, providing a summary of the learning pathways and highlighting students’ learning as it related to classroom processes. I continue with the case group and present their learning pathway for Ina based on her responses in Chapter 5, given her overall improvement in learning and comprehensive engagement with the tasks. I also reference class-level responses where appropriate.

7.2.1 Understanding students’ prior knowledge and establishing the context (Modules 1–4)

The first four modules introduced the context through engaging students’ prior knowledge, providing broad canonical information about climate change and the greenhouse effect (related to pre- and post-test items Q7 and Q10), introducing some of the digital tools in STILE (e.g., live poll, concept map). In response, the case group used these tools to express their prior knowledge about energy and their ability to relate it more broadly to the planet (see Figures 5.1 and 5.2). Their attitudes about climate change were consistent with the class,
suggesting an interest in the topic (see Module 2). The remaining modules were more conceptually and representationally focused, providing more detailed insight into students’ learning.

7.2.2 Temperature and thermal energy (Module 5)

Module 5 began with a survey of students’ prior knowledge of the particle model (see Appendix B), included two representational challenges incorporating particle ideas, and concluded with a multimodal summative assessment. Ina’s learning pathway is depicted in Figure 7.11 and indicates important shifts in her ideas and ability to represent them across this module. All three students in the case group scored 28.5% on the survey, below the class average, though their responses were not necessarily the same. At a class-level, the most consistent responses were for Q4, with 77% of the class responding correctly to ideas related to the conservation of matter. Conversely, 81% of the students responded incorrectly to Q1, which stated all freezing substances have to be below 0°C.

The following incorrect responses related to the key ideas of this module including kinetic energy, changes of state, atomic structure, and temperature: 62% of the class indicated that molecules in a solid were stationary (Q5); 58%, including the case group, indicated that wax molecules change texture when melting (Q3); 46%, including Ina and Megan, indicated there was air in spaces in between atoms (Q6). Only 42% of the students, including Ina, responded correctly to the idea that it was possible to heat an object to +1000°C but not cool it to -1000°C (Q2). Though none of these questions related the pre-test questions, they focused on the particle theory of matter, which was a conceptual focus across these next three modules, suggesting students had limited prior knowledge of this topic with alternative conceptions.
The next activity was the first guided series of representational challenges (see Figures 5.5 and 5.6). The case group presented a variety of digital representations incorporating many of the intended criteria. Their responses indicated the first shift in RC compared to their pre-test responses: The case group went beyond the macroscopic (i.e., Level 1) to depict particle ideas using symbols and annotations, in addition to relating two representations (i.e., Level 4).

Until this point, students were only generating static representations. In Activity 5.3, students experienced their first actional mode, demonstrating a lump of plasticine at two different temperatures through role-plays. The case group did not show movement of particles at lower temperatures, reflective of Ina’s and Megan’s responses in Activity 5.1 where they indicated solids were stationary (Q5) (see Figure 7.11). Following this activity, students engaged in their second representational challenge as an EGR-SGR interplay, viewing their first purpose-made video about particle motion (see Figure 5.9), then representing particles as solids, liquids, and gases in the STILE platform (see Figure 5.10). All three students were able to express the idea of particle motion in all three states, signifying a shift in understanding. In addition, Ina was able to express the idea of motion in her written response, whereas Megan and Clara indicated motion in their diagrams and related their text to their diagrams, showing a Level 4 RC.

The final activity in Module 5 presented the second purpose-made video (see Figure 5.11), followed by a summative task for the module (see Figure 5.12). For Q1, all three students indicated the change in movement using either digital text or annotated diagrams, consistent with their shift in understanding of particle motion in solids. Ina and Megan’s representations also depicted differences between the two scenarios, though Ina’s were less clear. Ina and Megan related
their text to their diagrams, indicating a Level 4 RC. Though Clara only provided text, her explanation was consistent with scientific ideas.

The other questions in this activity presented hypothetical scenarios in everyday contexts. For example, Q2 was: “Explain how an ice cream that is at 4°C can have thermal energy”, related to the concept that all matter on Earth has thermal energy. All three students indicated correctly that there is motion in even a cool solid, supporting their shift in conceptual understanding from their responses in the pre-test Q1 and Activity 5.1 Q5. Ina’s response included additional information from the video:

All objects with a temperature above -237 degrees (sic) have kinetic energy, but when in cold temperatures the particles move slower than a hotter temperature. The motions (sic) from the kinetic energy and the energy between them is the thermal energy.

Though the temperature at zero degrees Kelvin was written incorrectly, Ina’s response showed an awareness of the lowest temperature for matter, consistent with her response in Activity 5.1 Q2. Ina was able to correctly attribute motion to kinetic energy and relate it to thermal energy, but did not specify that thermal energy is the total amount of kinetic energy resulting in a measurable temperature. Overall, all three students showed an improved understanding of particle motion and thermal energy and were able to apply their ideas in different contexts.

**Summary of Module 5**

Though the case group’s responses to the 5.1 quiz indicated alternative conceptions in energy transfer, they did make some progress throughout the written and representational activities. The most noteworthy shift related to
particle representation in Activity 5.2, where their RC subsequently depicted submicroscopic processes, showing an improvement from their pre-test open-ended responses. The case group also shifted their ideas about particle motion and thermal energy. Their understanding of particle movement in solids changed in response to the video in Activity 5.4, and through re-representing these ideas across modes in Activity 5.5. To achieve this: they first expressed their ideas in text (pre-test Q1, Activity 5.1 Q5); learned how to draw particle diagrams (Activity 5.2); expressed their ideas through a role-play and reflected on these in text (Activity 5.3); re-represented their ideas in response to the canonical information provided in the EGR-video (Activity 5.4); and re-represented and applied their ideas in another context (Activity 5.5). The \textit{constellation of modes} included text, visual, and actional modes, indicating the importance of cross-modal translations in supporting conceptual change (Airey & Linder, 2008).

Further, students experienced two representational challenges, which organised cross-modal translations around a specific conceptual focus. Students’ strongest learning gains took place after they viewed the video and re-represented their ideas, suggesting an important role for dynamic representations and EGR-SGR interplay, which is explored in subsequent modules.

Figure 7.11 demonstrates the sequencing and interrelations of representations through Ina’s responses. The sum of her representations to explore energy transfer through multiple modes (e.g., textual, visual, actional) and representational forms (e.g., written text, drawings, role-plays) resulted in a more comprehensive understanding of the concept (Lemke, 1998b). The multimodal activities afforded by the DLE enabled students to express a more sophisticated understanding about energy transfer in context through a variety of...
representational forms (Waldrip et al., 2013b). Students’ RC was also correlated with these shifts in understanding, showing an ability to represent submicroscopic processes (i.e., Level 3) and relate meaning between textual and visual forms (i.e., Level 4).
Ina scored below class average. The items that more closely related to unit were: Q1, 2, 5, 7. For Q1, her response was incorrect and reflective of her pre-quiz response regarding thermal energy (Q1). She responded correctly to Q2. For Q5, she indicated that solid particles were stationary (Q5), indicating persistent alternative conceptions. For Q7, her response regarding particle collisions in energy transfer was incorrect (see Appendix B).

In her first formal introduction to SGRs integrating particle ideas, Ina was able to depict submicroscopic particles and connectedness for all relevant challenges. She integrated colour for Challenge 5 and annotations for Challenge 6. She did not strongly distinguish the fragile bonds of the chalk. Overall, her RC was Level 3, an improvement from her pre-test open-ended responses (Q8–10) (see Figure 5.6).

Despite the dynamic affordances of the role-play, Ina was still not expressing particle motion in solids at lower temperatures, consistent with her incorrect response in the pre-test Q1 and Activity 5.1 Q5.

The EGR-NSGR interplay between the video showing animations of particles of substances in different states, and all three students’ representations reflected a learning gain. Even though Ina’s response was written, she indicated particle connectedness in all three states, and for the first time, described movement in solid particles, indicating a shift from her response in the pre-test Q1 and Activity 5.1 Q5 (see Figure 5.10).

In Q1, Ina represented connectedness and motion in particles for both scenarios, with changes only in spatial configuration and bonding. She represented submicroscopic processes and related the text to the diagram, indicating a Level 4 RC. For the remaining question, she was able to apply her understanding in context, relating kinetic energy and thermal energy (Q2), a shift towards improved understanding since the pre-test (Q1) where she indicated there was no kinetic energy in a piece of cold metal (see Figure 5.12).

Figure 7.11. Sequence of representational products and classroom processes in Ina’s Learning Pathway: Temperature and thermal energy (Module 5).
7.2.3 Heat transfer through conduction (Module 6)

Video capture commenced from this lesson, allowing for VSRI to be included in the analysis. The case group showed chaotic learning progressions in this module, maintaining some of their gains from the previous module, developing conceptual knowledge, and reverting back to previous alternative conceptions. Module 6 featured another role-play and the first practical investigation in the multimodal learning sequence (see Figure 7.12). Students began the module by comparing energy transfer in conductors and insulators using role-plays and re-representing their ideas in diagrams, as impromptu activities added to the lesson sequence due to technical issues with the video projector. Though the case group did not demonstrate particle collisions in insulators during the role-play, they were able to depict this idea in their diagrams. In the VSRI, Ina explained how they demonstrated heat: “So that’s me starting it [pointing to the part of the video when Ina initiates movement] and giving the next person the heat, sort of. And then there’s movement.” Ina correctly identified heat moving through the particles and was beginning to make the link between the heat and movement (i.e., kinetic energy). Megan elaborated on the mechanism of energy transfer in response to the follow-up question in STILE:

When the particles are placed together because they bump together, they all start moving really fast because, because...they start moving. I start moving because I’m really close to the heat. But in the insulators, I think the particles are further apart so they are still moving together, but they are not bumping into each other as much. They are not moving as much.
Megan expressed an understanding of the direction of energy transfer along with the differences in the rate of particle collisions between the two scenarios.

The case group’s diagrams (see Figure 5.13) incorporated particle motion, indicating that they maintained their learning gain from Module 5 (see Activity 5.4 and 5.5 Q1). All three students generated diagrams depicting submicroscopic particles and movement and used the constructive resource of colour to indicate heat. They also represented spatial differences between the two materials. In contrast to their role-play, both Ina and Clara also depicted particle connectedness in the insulators, though Megan did not. All students provided annotations as directed, with additional symbols to indicate movement. Megan’s annotation, “spread through by collisions” showed a clear connection with the ideas presented in the EGR-video. All three diagrams indicated a Level 4 RC as they related the text to the diagrams.

In addition to her annotated diagram, Clara wrote the following explanation in her project book: “Conductor: the particles are closer together and viabrates (sic) quickly because they’re closely packed. Insulator: the particles are more spread out”. Her explanation elaborated on the spatial difference of particles in conductors and insulators; however, she attributed kinetic energy with density, omitting the role of heat affecting the kinetic energy and movement. Her spontaneous addition of a written explanation relating to the diagram suggested Level 4 RC.

During the VSRI, I asked the group to compare how the role-play and diagrams supported their learning:
Megan: In a role-play, you can see the movement. You can see how the particles move. Whereas in a diagram, you can draw it, but you can’t make the particles move.

Connie: Any other comments?

Ina: Having the other groups do it as well, helped, because we could see the movement.

Megan and Ina referred to the affordances of the role-play for expressing and viewing movement, indicating a reflective use of representation (i.e., Level 5 RC). Though they mentioned the constraints of diagrams, the case group represented movement diagrammatically by using brackets (see Figure 5.13), indicating a high level of RC across modes.

Students then viewed a series of videos, followed by questions in STILE (see Activity 6.1 in Chapter 5). The first video was purpose-made and elaborated on conduction, connecting the macroscopic and submicroscopic processes (see Figure 5.14). Following the video, students applied their understanding to different contexts involving particle collisions that results in energy transfer and why they occur: “a) less in substances that contain pockets of air than in solid substances? And b) less in solid non-metallic substances than in metallic substances.” Ina responded in STILE:

a) The air in insulators, blocks the particles from colliding – meaning heat is not continuing to move. Solid substances have no air pockets, which means the particles are free to collide and continue transferring kinetic energy. b) Metallic substances might be more compacted, which means the particles are closer together, and when they move around they have
less space to move in – meaning collisions happen more often, spreading the kinetic energy faster.

The correct response should indicate particle collisions are slowed, thus heat transfer proceeds at a slower rate. Instead, Ina incorrectly stated that air blocks particles from colliding rather than just slowing the transfer of energy. She also stated that solids have no air pockets, but did not mention the spatial configuration of particles in difference substances. Her response to part b) attributed the particles being closer together in metals resulted in more collisions and faster transfer of kinetic energy, which was partially correct. Compared to the role-play, she was now using the term kinetic energy to describe movement. Megan’s response indicated that in both cases, particles were less compacted so did not bump together as much. Clara attributed the compactness or density of particles to affecting the rate of movement and collisions. Overall, students’ application of their understanding in these scenarios indicated they had incorporated the idea of kinetic energy transfer using particle ideas with some inconsistencies in their understanding.

The next video presented people’s informal understanding of conduction based on everyday contexts. Students reflected on if and how their own views changed based on evidence. Ina wrote:

As I was watching the video i (sic) firstly agree with the people being interviewed, but as it continued and as he was baking the cake, i (sic) thought about conduction and felt that maybe the cake and the tin were the same temperature, metal just conducts heat faster. I now agree with the scientist in the video, as he clarified what I was thinking. b) I think that when a cake is taken out of the oven, it is brought into a much cooler
environment than it was in before. The tray cools down faster than the cake, because it is directly being moved into the cooler temperature, whereas the cake is inside the tin, and still get the heat from the tin, while still feeling the heat at the top.

The question presented an everyday context for conduction and provided an opportunity for students to reflect on their learning, a departure from a focus on propositional knowledge, which is often overemphasised in classrooms (Klein, 2006). Ina’s response reflected a change in her understanding of conduction. She explained that once the cake is removed from the oven, the tray cools at a faster rate than the cake, which was consistent with the canonical explanation. She also incorrectly explained that the heat from the tin continues to warm the cake, making the cake warmer than the tin over time. This is partially correct in that the cake does stay warmer than the tin, but it would be due to the slower rate of cooling. In addition, it was not clear if Ina attributed these behaviours to conduction or insulation. She did not provide a mechanism by which the energy transfers other than to state that the tray was moved to a cooler temperature.

Megan indicated that “the tray cools faster because it quickly absorbs the temperature outside of the oven and becomes cool”. This implied a net energy shift but was still suggestive of her idea that coldness transferred (see pre-test Q3). Similar to Ina, Clara indicated that the tray conducts heat faster resulting in it cooling down faster. With a focus on an everyday context, students applied their ideas to each scenario and were given the opportunity to consider the other perspectives, their own perceptions, and a chance to revise their thinking based on the evidence presented. All three students initially identified with the alternative conceptions presented by the interviewees in the video. This sequence followed a
constructivist perspective – a departure from simply just designing questions for a single *right* or *wrong* response, eliciting the affective domain, consistent with contemporary views of learning (Klein, 2006).

There were three additional MCQs presented as a summative task, integrating the key ideas in this module (see Appendix C). All three students in the case group had scores of 33%, below the class average of 50%, though their responses were not necessarily the same. Question 3 related to the iron-rod scenario presented in the pre-test and revisited in the first Module 6 video on Conduction. Most of the class chose the correct answer (65%), including Ina. Ina’s response to Q3 was consistent with her earlier understanding that energy transfer takes place in the direction of greater to lesser heat (see pre-test Q2 and Q8). However, both Megan’s and Clara’s incorrect responses were consistent with their pre-test Q2, though they were able to correctly express the direction of transfer in the pre-test Q8, suggesting they still had challenges with this concept.

Q4 related to energy transfer from a hot frying pan placed on the counter and gradually cooling to room temperature. Seventy-five percent of the class responded incorrectly, including the case group, who indicated coldness transferring (see pre-test Q3). As a class, the best result was for Q5, with 70% of the class responding correctly, including Megan and Clara. This question was of similar nature to the cake and tray scenario presented earlier in the unit, where all three students indicated their changed ideas about conduction through different materials. Interestingly, Ina’s incorrect response to Q5 contrasted to her earlier learning gain within the same module, indicating inconsistent understanding across contexts.
The final activity was the Heating Investigation. Students explained their results (see Figure 5.15). Ina predicted that the covered probe “would heat faster and reach a higher temperature than the other uncovered probe”. Megan’s response presented a possible explanation: “My prediction was incorrect, the covered probe didn’t heat up as much as the uncovered, so this means the foil used must be an insulator”, suggesting that she incorporated some of the ideas presented in this module.

Summary of Module 6

The case group showed some learning gains around particle movement in conduction, but were inconsistent in applying these ideas to different scenarios (see Figure 7.12). Their initial gains were linked to their first translation activity across modes (i.e., from role-play to diagrams), with post-EGR-video written reflections (Activity 6.1) resulting in the most consistent gains for all. In addition, the group expressed an awareness of the modal affordance of the role-play. However, there remained inconsistencies in explaining energy transfer in insulators. In the final series of MCQs, the case group reverted back to their initial alternative conceptions about coldness transferring and rates of energy transfer in different materials, suggesting a chaotic pattern of learning across the modules. The first practical investigation also had mixed learning gains. However, it did not provide representation-focused questions. The constellation of modes was similar to that in Module 5, and included a translation sequence and a practical investigation, but involved less SGR activities.

Figure 7.12 demonstrates Ina’s responses to this representational sequence, showing her representational experiences to include a role-play, a drawing, a video, text-based and closed-ended multiple choice responses, and a
practical investigation followed by text-based responses. Compared to their pre- and post-test responses, the case group showed limited but the most consistent learning gains in conduction and the highest levels of RC compared to the other concepts. The video-based EGR-SGR interplays with the iron-rod scenario in Module 5 (see Figure 5.11) and Module 6 (see Figure 5.14) presented two opportunities for students to directly relate canonical information to representations, and likely contributed to their relative improvement in their post-test Q8 representations.
Ina was part of a group that demonstrated the differences in heat transfer between conductors and insulators, showing particle motion in both cases. However, for the insulator, they did not show particle connectedness or a mechanism by which the energy transferred through particle collisions.

Students re-represented their role-play as a diagram. Ina represented both connectedness and movement in both examples, addressing the omissions in the role-play, and retaining learning gains from Module 5.

In her diagram, Ina included symbols, annotations, submicroscopic particles, and constructive resources such as colour and visuo-spatial attributes. Overall, her RC was Level 4 (See Figure 5.13).

During the VSRI, Ina identified the heat moving through particles and was beginning to make the link between heat and movement (i.e., kinetic energy).

Ina expressed an awareness for the affordances of the role-play in that she could see the movement.

Students viewed the purpose-made video relating the macroscopic iron rod scenario in pre-test Q8 to the submicroscopic processes of conduction (see Figure 5.14).

After viewing this video, Ina was now relating kinetic energy and heat transfer, building on her ideas expressed during the role-play, and indicating a shift since her pre-test Q8 where she saw them as two separate processes. She correctly explained that faster transfer of kinetic energy in metals was due to more collisions; however, she also attributed it to particle compactness.

For insulation, Ina stated that air blocks particles from colliding instead of just slowing energy transfer, and that solids have no air pockets. Ina’s reflections about the second video indicated that she now understood conduction happens at different rates for the tin and the cake but did not provide a mechanism.

Ina scored below class average (see Appendix C).

Her response to Q3 was consistent with her responses in similar items in pre-test Q2 and Q8: that energy transfer takes place in the direction of greater to lesser heat.

Her response to Q4 suggested that she reverted back to her pre-test idea that coldness transfers (Q3).

Her response to Q5 indicated she reverted back to her previous ideas about conduction through different materials, as expressed in the cake and tin example in Q2. This suggested she had difficulties in transferring knowledge across different contexts.

Ina’s prediction did not reflect the outcomes of her group’s investigation; however, she provided no explanation (see Figure 5.15).

Ina was part of a group that demonstrated the differences in heat transfer between conductors and insulators, showing particle motion in both cases. However, for the insulator, they did not show particle connectedness or a mechanism by which the energy transferred through particle collisions.

<table>
<thead>
<tr>
<th>Role-Play</th>
<th>Representational Challenge</th>
<th>Discussion</th>
<th>6.1 Representing Conduction</th>
<th>6.1 Representing Conduction (Q3-5)</th>
<th>6.2 Heating Investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students create a role-play demonstrating how heat transfers in a conductor and insulator.</td>
<td>Students draw representations depicting heat transfer in a conductor and insulator.</td>
<td>Students participate in a video-stimulated recall interview and reflect on their role-plays and diagrams.</td>
<td>Students view a video explaining key concepts in conduction.</td>
<td>Students address questions on different scenarios in conduction.</td>
<td>Students use dataloggers and temperature probes to compare differences in heating.</td>
</tr>
</tbody>
</table>

Figure 7.12. Sequence of representational products and classroom processes in Ina’s Learning Pathway: Conduction (Module 6).
7.2.4 Heat transfer through convection (Module 7)

Compared to the previous module, the sequence of activities for Module 7 included more diagrams, which were directly related to a video-based EGR-SGR interplay and a practical investigation (see Figure 7.13). After a short introduction to the unit, students viewed a purpose-made video about convection (see Figure 5.16), then generated three representations through an EGR-SGR interplay. In the first one, students followed the same conventions symbolising convection currents presented in the video (see Figure 5.18), which they applied to the other two representations (see Figures 5.19 and 5.20). These two questions provided an image of a candle and furnace, focusing students’ attention on the currents. All three students were able to correctly depict the direction of the convection current. Ina and Megan included particle explanations that depicted motion but were inconsistent with connectedness (see Figure 5.19). For the water heater (see Figure 5.20), Ina and Clara were able to correctly depict the flow of cold and hot water, whereas Megan’s diagram suggested some confusion with the cold water exiting the heater. None of the students indicated the hot water outlet in their diagrams, though Megan and Clara clearly showed where the hot water was exiting using red arrows.

After an impromptu demonstration about convection currents, students conducted a practical activity. After some teacher-led scaffolding, they experienced their first post-activity mapping activity where they constructed a representation to explain how energy was transferred in the teabag rocket. This two-way mapping from the observed phenomenon to representation provided a stronger conceptual focus to the practical investigation, addressing a the issue of limited conceptual learning in activities (Hofstein & Lunetta, 2004). Ina and
Megan followed the same symbolic conventions as they did throughout the module (see Figure 5.21), with responses that indicated their uptake of the teacher’s guidance in this activity and the EGR-video presented at the beginning of the unit. Both related text to their diagrams, indicating a Level 4 RC. Clara did not respond.

**Summary of Module 7**

Compared to the pre- and post-test results, students’ learning gains and RC were the most limited, with persistent alternative conceptions about coldness transferring (Q3) and some improvement in understanding the direction of heat transfer (Q5). Though their initial representations followed the symbolic convention introduced in the EGR-video, their final one was a student-generated and refined representation in response to the mapping task. Both Ina and Megan correctly depicted the flow of the convection currents. Yet, for the post-test, only Clara incorporated arrows in the post-test mitten-snowball scenario (Q9), possibly indicating that the other students did not equate this question with convection. Though the complexity of the Q9 likely resulted in students’ limited responses, their MCQ responses also indicated challenges in understanding convection. Figure 7.13 is a summary of Ina’s responses to the EGR-videos and the practical investigation, demonstrating a strong canonical influence throughout her responses and a refined post-activity mapping SGR.
After viewing the purpose-made video on convection (see Figure 5.18), student engaged in EGR-SGR interplay. Ina constructed a representation that resembled the one featured in the video (see Figure 5.18). Her annotated diagram included the use of symbolic arrows to depict the flow of air, indicating a Level 2 RC.

Ina drew a convection current with warm air rising and cool air sinking (see Figure 5.19). In her close-up diagram, Ina incorporated particle ideas showing heat rising through convection and changes to states of matter in fluids, but did not represent the cooler air in this current. The use of symbols and particle ideas indicated a Level 3 RC.

Ina correctly depicted the flow of cold and hot water (see Figure 5.20). She added arrows to the diagram, indicating the position of the cooler water intake, and the warm water rising, indicating a Level 2 RC; however, she did not indicate the position of the hot water intake.

Ina participated in the teabag rocket activity with her group. For this two-way mapping activity, Ina drew an annotated diagram to explain the convection current in the teabag rocket (see Figure 5.21). She used arrows to represent the flow of the current in relation to the heat source and related text to diagram, indicating a Level 4 RC.

Figure 7.13. Sequence of representational products and classroom processes in Ina’s Learning Pathway: Convection (Module 7).
7.2.5 *Heat transfer through radiation (Module 8)*

The final conceptual module introduced a considerable body of canonical information at the beginning of the representational sequence compared to the previous modules, providing limited opportunities for SGRs and hands-on activities (due in part to the exclusion of 8.4 and 8.5). The module also presented wave ideas to explain radiation, a departure from the particle model (see Figure 7.14). Students’ initial questions about the topic suggested they had limited knowledge of radiation (see Figure 5.22), reflective of their pre-test responses (Q6, Q7, Q10).

After viewing the purpose-made video about radiation, students learned how to construct representations using the wave model as part of an EGR-SGR interplay (see Figure 5.24) where they compared a radiowave and a microwave (Activity 8.1 Q1). Ina represented a different wavelength for each of the microwaves, which was inconsistent with the canonical ideas; she also represented the difference in amplitudes, which was consistent with the *strength* of the signal. Megan’s representations were consistent with the canonical ideas for wavelength and amplitude. Clara provided annotations, identified the electrons, and included arrows similar to the ones in the video to signify the direction movement of the waves. Like Megan, her representations were consistent with the canonical ideas about wavelength and amplitude and contained more ideas incorporated from the PhET animation in the video. All representations featured submicroscopic processes of radiation, indicating a Level 3 RC.

Students then viewed a generic video about electromagnetic radiation and participated in a follow-up fill-in-the-blank activity as a whole-class discussion.
The other SGR-related activity was a representational challenge that required students to coordinate representations to explain electromagnetic radiation based on a series of prompts provided in the question (see Figure 5.25). Ina and Megan created a PowerPoint slideshow about X-Rays. In the following lesson, they presented their slides during our interview:

**Ina:** Yeah. OK, so we did x-ray machines. And so this is where we got our information about where it is, the frequency and stuff. Like off the image that was on STILE. And so it’s a high frequency and it’s in between the radioactive elements and the ALS. Which I wasn’t really sure what that was, but it was a question I needed to ask. And it’s 10 point eighteen? I’m not sure that how you say it.

**Connie:** Ten point one eight.

**Ina:** Ten point one eight waves per second. OK, you wrote this slide [pointing to Megan]?

**Megan:** OK, we got these questions off the STILE, the answer in the… the natural sources we found we were not too clear on, but we thought we’d better answer the question. So, they’re the natural sources of this kind of radiation, the x-ray radiation. And then that’s a few of the artificial sources we found.

Their responses indicated they interacted with the information in a superficial way. Despite their lack of understanding, they were able to identify relevant information from the internet and construct a digital presentation. I then asked them how they understood conduction, convection, and radiation. Megan responded:
Megan: Well, we haven’t done so much on radiation yet so we don’t know as much. We are still understanding. Also, I find that radiation is not as like visual. Like you can understand with convection and conduction and all that, you can see, you know with the diagrams the particles you can see what’s happening. Whereas you can’t see that so much with radiation.

Despite engaging in a full lesson about radiation with videos, SGRs, and a digital presentation, students indicated they had not learned as much as they did with conduction and convection. They proceeded to discuss how participating in role-plays supported their learning:

Ina: ….and just like we did the play, like the role-play, that like helped understand. With radiation, it kind of was sort of hard to do a role-play.

Megan: To understand visually.

Ina: To see it really helps...to actually see it. And to see someone else do it as well.

This was the second time in an interview that students from this group mentioned role-plays (see the Conduction Module), suggesting a strong impact for this mode. In my interview with Clara and Anna about their mind map, they also used the questions as prompts and mentioned the visual attribute of their mode of representation (see Figure 5.26).

Summary for Module 8

Students’ post-test results indicated a limited improvement in their understanding of radiation in the MCQs and diagrams. Although all three students understood that objects emitted radiation (Q4), they each had varying degrees of understanding of energy transfer through radiation (Q6). Ina maintained persistent alternative conceptions, Megan showed improvement, and Clara was consistent.
They were also challenged by the greenhouse effect (Q7), with all three showing persistent alternative conceptions or inconsistent understanding. The issue of the missing activities in 8.4 and 8.5 likely impacted both their conceptual understanding and ability to represent these ideas, which was evident in their open-ended responses (Q10). The complexity of this question was addressed earlier in this chapter. Figure 7.14 shows the representational sequences, across written and visual modes, with no experiences of the actional mode or a hands-on activity. The representational challenge involved the generation of text with some coordination of text and images.
Ina generated four questions about radiation based on the key ideas of the module, suggesting limited prior knowledge of the topic, consistent with her pre-test Q6, Q7 and Q10 responses (see Figure 5.22).

The whole class viewed a purpose-made video about infrared radiation, and the teacher highlighted key features (i.e., the EM and the PhET animation) (see Figure 5.23).

Ina represented different wavelength amplitudes for strong and weak microwaves, consistent with the strength of the signal. However, the wavelengths were also different in length, instead of being equivalent (see Figure 5.24). Ina represented the submicroscopic process of radiation, indicating a Level 3 RC.

After viewing a video about the EM spectrum, the teacher provided several examples of radiation while the class listened. There was no record of Ina’s work.

Ina and Megan used Google Slides to construct their digital presentation, addressing each of the guiding questions and featuring written and digital modes (see Figure 5.25). They used images and symbols, indicating a Level 2 RC.

Through the discussion, Ina exhibited only a superficial understanding of radiation, guided by the information on her group’s slides. However, she expressed a reflective understanding of the role of representations to support her learning. In particular, Ina indicated the visual nature of a role-play in supporting her learning.

Figure 7.14. Sequence of representational products and classroom processes in Ina’s Learning Pathway: Radiation (Module 8).
7.3 Chapter Summary

By the end of the unit, the class demonstrated statistically significant learning gains in the MCQ (from 43% to 53%); the case group showed improved and varied conceptual understanding and representational competence. There were variations in their MCQs and open-ended responses, with conceptual understanding ranging from 0.5 to 3.5 points and RC levels ranging from 1 to 4. Using DCog theory to relate students’ responses with the activities and representational resources provided insight on the impact of the learning sequences in supporting meaning-making processes.

For the case group, the strongest learning gains as measured in the pre- and post-tests was in their understanding of thermal energy (Q1, Q8) and conduction (Q2, Q5, Q8). These learning gains were consistent with their responses in the related modules (i.e., 5, 6). These modules featured initial activities eliciting students’ prior ideas, a constellation of modes where the case group represented and re-represented their ideas across the written, visual, and actional modes (e.g., role-play representations, a translation activity from role-plays to drawings), and representational challenges around particle-level SGRs. These modules also presented the EGR-video later in the learning sequence, with the conduction video linking canonical information to the specific contexts, including that of the iron-rod scenario (Q8).

The weakest learning gains for the case group were in convection (Q3, Q9) and radiation (Q7, Q10), with persistent alternative conceptions and instances of decreased conceptual understanding and representational competence in their open-ended responses. These concepts were linked to Modules 7 and 8 where EGR-videos were presented at the beginning of the unit, with no initial activities
eliciting students’ prior ideas. In addition, though the EGR-videos in these modules related these concepts to everyday contexts, they provided a less direct connection to the respective test questions, requiring students to translate their ideas in particularly challenging contexts. Neither module featured an actional mode for representations (e.g., role-plays). Though Module 7 featured a post-activity mapping of SGRs, there were no additional cross-modal activities in either module. Though Module 8 included a representational challenge, students relied on a more superficial interaction of mostly textual modes, compared with the more in-depth SGR-based exploration in Module 5. The exclusion of 8.4 and 8.5 resulted in students’ missing more interactive, multimodal, and contextual activities, likely impacting their overall conceptual understanding about radiation and the greenhouse effect.

The variations and improvement in the case group’s learning suggested a high level of engagement with the resources provided, along with their ability to generate digital and non-digital representations, and to apply their knowledge to an inquiry-task. The limitations in their responses across the conceptual units suggested the need for a carefully sequenced coordination of interactions across modes to support a robust conceptual understanding. As indicated in Chapter 5, the limited teacher-led discussion and assessment around SGRs likely impacted students’ overall learning gains in conceptual and representational development, including the early identification of possible misconceptions. The complexity of students’ learning pathways has implications for the design of the sequences to support students’ learning engagement in epistemic processes and is addressed in the Discussion Chapter.
The use of the pre- and post-tests also presented limitations for assessing students’ learning. While the use of closed-ended MCQs across the unit and in the pre- and post-test provided instant feedback on students learning, their open-ended responses provided more insight into their conceptual understanding (though neither of these were followed up on during the unit). If conceptual understanding is attributed to the sum of representations (Lemke, 1998b), then restricting assessment to the textual modes misses students’ engagement in these broader semiotic and epistemic process that are central to understanding scientific concepts. However, assessing multimodal representations presented other challenges: the link between conceptual and representational development, designing questions that require the need for multimodal responses, and the role of the teacher in making these links during instruction. These ideas are addressed in the Discussion Chapter.

Though the case and student-level responses were not necessarily indicative of the whole class, they were suggestive of the successes and challenges associated with learning energy transfer through representations in this digital learning environment. The Discussion Chapter builds on the key themes presented in Chapters 4 through 7 in relation to the potential of DLEs in supporting a representational-focused approach to learning science.
Chapter 8. Discussion

My investigation involved a study of a Year 9 science classroom in which an evidence-based inquiry pedagogy was integrated with an interactive online learning platform. The unit was created through a researcher-led design and delivered by a science teacher. The representation-focused learning sequences were intended to engage students more directly in the scientific disciplinary practices of knowledge construction to support their conceptual learning and engagement. This discussion chapter addresses the findings in relation to my overall research focus and my research questions.

Research Focus: to investigate how a Digital Learning Environment (DLE) designed with an inquiry-based Representation Construction Approach (RCA) engages students in learning science.

1. What were the generative features of this DLE in supporting an inquiry-based RCA?
2. How did the summative inquiry task support epistemic processes representative of scientific practice?
3. What were the patterns of conceptual and representational development in response to RCA in this digital environment?
4. What are the implications for the design of digitally-based RCA units?

This chapter is divided into five sections, addressing each of the research questions and the overall engagement of the students’ learning science.

8.1 Generative Features of the DLE (RQ1)

The DLE consisted of the teacher’s orchestration of activities across various media with digital technologies (e.g., laptops, online learning platform, videos, dataloggers) to scaffold and support learning sequences following a RCA.
Chapters 4 and 5 indicated the DLE provided flexible and expanded access to multimedia and multimodal representational resources. Students’ agency for constructing their individual learning pathways was supported through their flexible access to these resources. Chapter 4 also indicated a large amount of student-to-student dialogue to support the inquiry-based processes of RCA, though further analyses (Chapters 5, 7) revealed that the nature of the dialogue did not meet its full potential.

The notion of generative features emerges from the socio-semiotic and epistemic theoretical perspectives which underpin RCA. The term refers to dynamic processes involved in the construction of meaning and plans of action (Wittrock, 1992). For RQ1, generative features refer to affordances of the DLE for supporting active meaning-making processes. This section addresses the affordances of key digital media and the implications for expanded delivery options. I argue that the multiple media in this DLE expanded students’ access to representational resources and provided flexible guidance to support their engagement in the science-based semiotic and epistemic processes. In doing so, the DLE opened up possibilities for construction, coordination, and evaluation of representations. In addition, the online learning platform and purpose-made videos presented key digital affordances for RCA.

8.1.1 Flexibility, agency, and multimodal representational resources

The teacher’s orchestration of activities and the digital scaffolding of learning sequences guided students’ experiences of the unit. In response, students explored and negotiated meaning across a range of representations, building a multimodal conceptual understanding while engaging directly in the process of
knowledge construction; these processes were consistent with RCA and presented additional affordances through digital media.

Compared to non-cloud-based classrooms, the online learning platform provided flexible and expanded access to a richer semiotic environment. The platform enabled students to access a variety of tools (e.g., paper, interactive canvas, live demonstrations, videos, dataloggers, practical investigations) and to create and use a wider variety of representational forms (e.g., digital word clouds, drawings, data tables, role-plays) across verbal, visual, written, and actional modes of representation. Students moved flexibly through face-to-face and online interactions, accessing both digital and non-digital representational resources in almost equal proportions, often concurrently, indicating their uptake of these expanded resources and their preferences.

*The online learning platform*

The digital learning platform did more than just organise and store content, which are limitations for many platforms (Richards & Dede, 2012; Richards & Walters, 2012). It supported the sequencing of the interactive science pedagogy, activities, and resources. It expanded the learning environment by enabling flexibility and agency for student inquiry (see Craciun & Bunoiu, 2015; Longo, 2016) through the incorporation of open-ended tasks and greater choice of representational resources and activities. This enabled students to engage in personally relevant meaning-make processes that would have been impossible without digital resources.

The authoring capabilities of the platform enabled the researcher-led team to scaffold learning in a carefully planned sequence of open-ended questions (e.g., diagrams, expanded text-based responses), digital and non-digital activities and
resources, and hands-on practical investigations. The teacher’s role involved: introducing context for the topics; adapting the activities to suit the circumstances (e.g., inclusion of non-digital activities when internet was down) and the learners’ needs (e.g., inclusion of a live demonstration); and facilitating discussion around SGRs (though this was not fully enacted and is addressed later in this chapter).

The platform also provided flexibility and agency for students in constructing their learning journeys as a guided-inquiry. This contrasts with transmissive settings, where students largely follow a single pathway of learning often constrained by text-based content, closed-ended questions, and procedural activities (see Tytler et al., 2013a). As a result, students constructed distinctive learning pathways as indicated through their timelines (see Chapters 4), their personally shaped responses to individual, group, and whole-class activities (see Chapter 5), and their learning journeys (see Chapter 7). This degree of agency is consistent with studies in non-cloud-based classrooms where student pathways are individual and complex, require flexibility in their construction, and have no single conceptual pathway leading to understanding (Tytler & Prain, 2010).

Even more so than in non-cloud-based classrooms, students exercised agency through their choice of media (i.e., project books or online), digital tools (e.g., mind maps, PowerPoint presentations), and through their open-ended responses. Students also chose their partners and groups, though these remained fairly consistent. The RCA involves a high degree of agency for students to engage effectively with semiotically rich processes: allowing students to make choices based on their interests and abilities, and to represent and communicate their ideas using a range of resources as a “multimodal ensemble” (Kress, 2010, p. 25). The cloud-based platform extended flexibility, agency, and access to a
greater range of representational resources supporting a viable digital approach to
RCA.

Additional possibilities and challenges for online learning platforms

The online learning platform featured applications that supported the
digital construction of drawings, along with assessment and collaborative
practices. The interactive canvas enabled students to generate representations of
equivalent quality to ones in their project books. Despite this digital affordance, in
the Questionnaire, many students cited challenges with the Paint application,
suggesting the need for additional supports. Other applications expanded the
traditional close-ended multiple choice assessments through customised (i.e.,
automated instant) and visually-aggregated (i.e., live poll) feedback. Applications
also accommodated students’ open-ended multimodal responses through the
interactive canvas and the infinitely expanded ruled pad for extended written
responses. The platform also collected students’ digital and uploaded responses
for each question as a repository of their learning. However, apart from
downloading and organising selected responses, there was no way to aggregate
students’ responses to individual challenges or questions to publicly compare and
contrast for discussion and assessment. An aggregation tool for SGRs for each
question would support whole-class negotiations. Finally, a class discussion
application was available in STILE, though it was only used informally by
students for off-task conversations. A more intentional use could support
asynchronous online student-to-student communication to support collaborative
tasks.

Compared to the complexities of designing web-adaptive (Panjaburee &
Srisawasdi, 2016; She & Liao, 2010) and digital collaboration platforms such as
wise, Knowledge Forum and Group Scribbles (see Linn et al., 2003; Quintana et al., 2004), STILE presented an accessible (i.e., cloud-based, easy to use) digital authoring tool for collaborative design and teacher-led implementation of an interactive teaching approach. Expanded use of assessment applications (e.g., live poll), more intentional use of the current applications (e.g., Class Discussion), and the development of an aggregation tool would support more generative interactions within STILE.

Finally, along with the realised and potential affordances of digital tools come the challenges. In my study, there were issues with connectivity which influenced accessibility to the cloud-based activities and resources. These ongoing issues are common with internet-based resources (Kyei-Blankson & Ntuli, 2014; Longo, 2016). My study also demonstrated additional demands for the design and delivery of this unit, involving the collaboration of researchers and teachers, along with training for the cloud-based platform. These demands involve the need to develop and manage effective online curriculum (Christensen et al., 2013; Garrison & Vaughan, 2008), and in particular, the need for the teacher to orchestrate cohesive learning experiences across the digital and non-digital domains (Wise & Shwartz, 2017). These challenges are consistent with research indicating the importance of collaborative design and implementation teams, and the ongoing role of revising and refining digital innovations to support quality learning outcomes (Kyei-Blankson & Ntuli, 2014; Wu & Wang, 2016).

**Extending the DLE to a fully blended learning environment**

The movement towards increasing BLEs in secondary core subjects like science (Christensen et al., 2013), along with the high home-use of computers and the demand for more productive integration of ICT (OECD, 2015a) suggests the
need for viable disciplinary-specific models. Though most of the interactions in this DLE took place in the classroom setting in the presence of the teacher (except for homework), the digital affordances demonstrated by STILE suggested the possibility for a generative delivery through a fully blended model, where learning sequences are completed outside the classroom as part of a cohesive unit. I argue that a BLE model increases students’ autonomy through flexibility, agency and collaborative options beyond the classroom-based DLE, while supporting the role of teacher-led facilitation for this guided-interactive approach.

My findings indicated that the cloud-based platform supported the guided-inquiry approach, enabling the teacher to orchestrate the learning sequences and tasks to accommodate more open-ended responses. These affordances are consistent with blended science approaches for supporting science inquiry practices (Bidarra & Rusman, 2017; Longo, 2016) in contrast to a fully online model, which would not accommodate this degree of guided practice (Means et al., 2009). The role of teacher-led guidance is consistent with RCA approaches and provides direct support necessary for younger learners (Longo, 2016; Means et al., 2009). In addition to this face-to-face guidance, a fully BLE could provide students with increased control and flexibility in the pace, time, and place of their learning (Bidarra & Rusman, 2017; Horn & Fisher, 2017). Similarly, BLEs have the potential to expand student choice in the mode of delivery and differentiation for individual learning needs (Kyei-Blankson & Ntuli, 2014; Longo, 2016).

While most of the interactions in my study were face-to-face, my findings demonstrated the potential for digital collaboration through Google Docs during the summative task. The case group chose this collaborative tool to construct their final report, where all three members accessed the document simultaneously to
elaborate and refine their ideas for the final report, resulting in a high-quality document (see section 6.4.1). Their process of writing involved shared authorship and editing, along with ongoing collaborative dialogue to clarify issues (e.g., constructing a data table). My findings are consistent with those concerning the productive use of Google Drive for online collaboration in science classes (Longo, 2016; Wise & Schwartz, 2017), and demonstrate that it has a potentially generative role in contemporary science BLEs. The coordinated use of both Google Docs and CD present additional affordances for accessibility and flexibility for students who are not able to attend class or are otherwise not as socially active in face-to-face settings. These collaborative technologies have the potential to support generative learning processes outside class time as a cohesive learning experience.

8.1.2 Videos as a generative digital resource

In addition to the online learning platform, the second generative resource was the purpose-made videos. While the videos were featured throughout the unit, the purpose-made videos in the conceptual Modules 5–8 presented specific affordances in supporting RCA. The videos combined multiple representations to explain concepts in the context of sustainable housing. The videos carefully sequenced static and dynamic macroscopic and submicroscopic representations focusing on particle and wave ideas, providing a relevant context for the concepts as a multimodal instructional resource for students (Gilbert, 2008). There were two specific design features that supported students’ meaning-making processes in their conceptual learning.

The first was the connection of the macroscopic and submicroscopic features. These connections were exemplified in the convection video (see Figure
5.14), which featured a macroscopic image of the iron rod scenario being heated at one end, followed by a PhET animation of how energy is conducted through the particles in the iron rod. These connections were also made in the convection video (see Figure 5.16), which featured a macroscopic image of boiling water in a saucepan, followed by an animation of the convection currents.

In response, the case group integrated some of the key ideas in their subsequent explanatory work. For example, after viewing the conduction video, students’ particle representations included movement along with some scientific terminology (i.e., kinetic energy) (see Figure 5.12). Similarly, after viewing the convection video, students’ subsequent representations indicated a consistent uptake of the abstracted currents in their representations (see Figures 5.18–5.20). These connections addressed one of the major challenges in learning about scientific phenomena: linking the macroscopic and submicroscopic features through representations (Johnstone, 1991). From a semiotic perspective, the strategic linking of material phenomena with representational systems demonstrated the translation across modes, something that is not done succinctly in many available resources.

Second, the sequencing of related static and dynamic representations in increasing complexity (e.g., the image of the iron rod followed by the animation of the iron rod) models transfer to new representational forms, how to relate representations, and how to apply concepts to different contexts, supporting a deeper understanding (Ainsworth, 2006, 2008). In addition, the video-narration also highlighted the key features of these EGRs, focusing on the form and function of each representation. Finally, the combination of realistic and schematic images and use of verbal cues in relating these sequential...
representations supported students in making these connections (Renkl & Scheiter, 2017).

The purpose-made videos provided a generative digital resource that supported students’ semiosis for deeper conceptual understanding by modeling the translation across the modes and relating concepts across the observable and abstract. My findings suggest the potential in this design, in contrast to some of the research which indicates mixed benefits for supporting conceptual understanding (Ainsworth & Van Labeke, 2004). The impact of the design suggest a need to develop representation-focused resources that follow similar guidelines to support deeper conceptual understanding.

8.1.3 Summary of generative multimodal resources

The DLE expanded access to representational resources, supported flexibility and agency, and provided resources and guidance for students’ engagement in the disciplinary knowledge construction processes. Two key generative resources were the cloud-based platform and the purpose-made videos. The extension of the cloud-based learning platform for the blending of synchronous and asynchronous learning has the potential to expand flexibility and agency while supporting key epistemic processes such as guided-inquiry approaches, teacher-facilitated discussions around SGRs, and collaborative knowledge construction. Purposeful use of collaborative tools within the platform and development of aggregation tools would support a fully asynchronous blended approach. The purpose-made videos followed design features to support the effective use of multiple representations and provided generative representational resources. However, issues related to the limitations in teacher-facilitated dialogue and the timing of the videos in the learning sequences affected
the quality of the learning. This has implications for the overall design and delivery of the unit, which is addressed in RQ4. The next section focuses on how the summative task supported the epistemic processes of science.

8.2 The Summative Task as a Collaborative Inquiry Experience (RQ2)

Chapter 6 demonstrated that the case group applied their conceptual knowledge about energy transfer to generate an explanatory account of their findings. Importantly, they showed a high degree of engagement in active knowledge-building practices of scientific inquiry, indicated by their collaborative reasoning across distributed interactions with multimodal representational resources. Further, their collaborative reasoning involved a progression from informal to formal reasoning processes across increasingly fixed representational forms as students explored, constructed, and justified their explanatory accounts.

While the students’ final report indicated positive learning gains through their ability to apply knowledge to this new context, their explanatory accounts demonstrated gradual and sometimes contradictory ideas over the duration of the three-day task. Their responses illustrate how the process of learning through scientific inquiry is more complex than traditional accounts indicate and more aligned with contemporary views of the complex nature of scientific discovery processes. In this section I argue that the students’ pathways of emergent understanding during this task are reflective of authentic science inquiry processes and open up opportunities for generative knowledge transfer.

8.2.1 Challenges and possibilities for practical investigations

As a central activity in science classrooms, practical investigations customarily do not meet the expectations of engaging students in genuine inquiry or helping students make conceptual links (Abrahams & Millar, 2008; Hofstein &
Lunetta, 2004; Toplis & Allen, 2012; White, 1996). This is largely attributed to the recipe-style approach to procedures and a focus on students’ producing the correct result (Abrahams & Millar, 2008; Hofstein & Lunetta, 2004). Suggested improvements include more purposeful integration of inquiry strategies that involve students justifying their claims with evidence (Abrahams & Millar, 2008; Hofstein & Lunetta, 2004). Other suggestions include making more links between topics and providing more open-ended tasks without known outcomes (White, 1996). While these broad suggestions were taken up in my study, they did not indicate what an inquiry might involve and how students might experience a more genuine engagement with scientific investigations. Research into what constitutes actual scientific practice has proposed a more dynamic set of interactions, challenging the traditional notion of a fixed scientific method with predictable outcomes, implying the need for reform towards more authentic classroom inquiry (Tytler & Prain, 2013b).

Interest in providing more genuine inquiry experiences in science classrooms has necessitated the exploration of actual scientific practices. Osborne (2014) describes science as a practice-based activity involving an ensemble of participants, institutions, disciplinary ways of talking, writing, investigation, and modeling for knowledge production; this involves an ongoing dialectic between knowledge construction and critique. Duschl and Grandy (2013) view the practice of science as an interaction between cognitive, epistemic, and social processes. They advocated for the use of modeling, visual representations, and peer interactions for knowledge construction, an approach more aligned with contemporary cognitive and socio-cultural perspectives. Further, the researchers have also suggested students should engage directly in science disciplinary
practices such as posing and refining questions, theories and models; collecting and analysing data from observations and experiments; constructing arguments; and using the discourses of science (e.g., talking, writing, representing phenomenon). RCA extends this direct engagement with epistemic processes to include active knowledge construction through the development of multimodal SGRs, which students use to justify their claims based on evidence (Tytler & Prain, 2013b).

While Chapter 6 argued that the case group engaged with the epistemic processes that eventuated in a concise explanatory account, the gradual, complex, and sometimes contradictory unfolding of students’ conceptual ideas challenged the notion of methodical scientific discovery processes. Pickering’s (1993, 1995) exploration of scientific practices indicates these more complex and contradictory processes are inherent to scientific discovery. I use Pickering’s analysis to argue that the summative task in this unit is reflective of an authentic process of knowledge construction.

The epistemic mangle

Based on case studies of scientific invention in physics, Pickering (1993, 1995) proposed that scientific practices involve an iterative and adaptive dance between humans, their conceptual ideas and technologies, cultural practices, and context, resulting in emergent and evolving understandings, technologies, and practices. The dance is the mangle of human and material agency influenced by unexpected results (i.e., resistance) and adaptation (i.e., accommodation), involving the revision or redesign of hypothesis, conceptual accounts, methods, and technologies. The mangle contrasts with the traditional view of science as a prescriptive method with predictable results (see Tytler et al., 2013c).
While Pickering’s (1993, 1995) exploration of the development of scientific ideas involved highly proficient scientists, the translation of this mangle into the classroom to support students’ authentic engagement with science would need to involve tasks with particular design features. Learning tasks would allow for uncertainties (i.e., resistance) and embed adaptive opportunities to challenge ideas and practices, along with enabling student agency through the practices such as flexible decision making and revision of ideas and practices. Designing such adaptive tasks provides a generative context for the application of knowledge to solve genuine problems, and more closely aligns with authentic epistemic processes in science (Manz, 2015).

Relating features of Pickering’s mangle (i.e., agency, resistance, accommodation) to the summative inquiry task, students’ responses to these built-in uncertainties resulted in an ongoing emergence and adaptation of conceptual explanations of results. The design of the inquiry-task enabled the case group to negotiate various points of resistance that influenced the development and refinement of their explanatory account of their results. The following analysis draws from Chapter 6 findings, with reference to the case group’s ideas as indicated by the transcripts. I outline how agency and resistance were supported and highlight the emergent adaptations and ideas regarding students’ predictions about their inquiry questions: *Does foil inside a wall keep a room cool in summer? Is foil inside a wall just as effective as having foil outside a wall?*

*Agency, resistance, emergence, and adaptations*

Students experienced more genuine inquiry processes in designing their investigation and developing an explanatory account of the results. In contrast to the more linear and procedural experience of classroom practical investigations,
students shifted back and forth in developing their hypothesis and responding to the embedded and emergent challenges. Each stage of the task presented instances of agency, resistance, adaptations, and emergent responses. I highlight some of these key responses, particularly as they related to the development of students’ predictions, hypotheses, and explanatory accounts of their findings.

In the planning stage, students exercised agency through their choice of inquiry questions and their design of the investigation. In response, their emergent collaborative dialogue around their inquiry questions involved the spontaneous use of the model house together with gestures, and indicated uncertainty and accommodation in response to this challenge. For the foil on the outside trial, their ideas were sometimes contradictory: from the foil attracting to absorbing the heat, pushing the outside light away, and keeping the house cool in summer (see Episode 1). For the foil on the inside trial, students’ deliberations indicated that foil would prevent heat penetrating the house, keeping it cool (see Episode 1). They never committed to a hypothesis and their written predictions were of a tentative nature (see Figure 6.3).

Without a clearly defined prediction or hypothesis, the case group began their investigation, where they continued to explain and refine their ideas through collaborative dialogue. In response to the ongoing visual results generated by the datalogger, students shared, critiqued, and refined their explanatory accounts, including verifying their predictions. They engaged in an iterative dance between technology and refinement of ideas. Emergent behaviours included the spontaneous generation of data tables and a presentation of their findings based on their data table (see Figure 6.8).
Students’ explanatory accounts gradually incorporated scientific terminology and mechanisms. In response to the increasing temperature in the first foil on the outside trial, students shared plausible mechanisms for the process: where the foil pushes, reflects, and bounces off the reflective surface (Episodes 5, 6). The foil on the inside trial resulted in some unexpected behaviours and uncertainty about their original prediction. The first trial showed the temperature was increasing, but there was confusion about the context being summer or winter and whether the temperature would be the same or hotter compared to the other treatment group (Episode 7). Though students could not immediately resolve these details, they indicated that foil on the inside acted like insulation, providing a mechanism for these results (Episode 10). The second trial showed an unexpected decrease in temperature, presenting resistance to their ideas, resulting in deliberations around whether or not they had the right treatment house or if there was an issue with the inside foil falling down (Episode 11). The temperature eventually increased and the students determined that they did not allow the cartons to cool sufficiently between trials. By the end of the experiment, the case group summarised their results, providing an explanation for the temperature decrease for the foil on the outside treatment: “because maybe they don’t attract to the heat and it reflects the heat” (Episode 13, line 5); and concluding that their results supported their hypothesis and predictions. Two key aspects provided resistance. The time-limited nature of the task provided ongoing resistance to their experiment, resulting in an ongoing debate about doing a third trial (Episodes 4, 11, 12). The time restriction also necessitated collaboration, much like scientific inquiry (Latour, 1999). In addition, the datalogger created
operational and interpretational challenges for the experiment and presented some unexpected outcomes with initial data (Episodes 4, 5, 6).

Students engaged in the collaborative construction of a written report, drafting sections according to their roles and responsibilities, clarifying details about each other’s writing and the construction of the data table, and resolving their explanatory account into a written statement. They wrote “having foil on the outside will reflect heat off the house, and foil on the inside will trap the heat inside, acting as an insulator”, clearly indicating the mechanism in their explanatory account. In the follow up interview, the case group indicated their results were “kinda opposite to what we originally thought” and conceded their initial confusion about both treatment groups (Episode 16). Throughout the investigations, students engaged in exploratory and cumulative dialogue as they shared and refined their ideas through this joint task (Mercer, 2004). These patterns of discourse have been linked in the literature to stronger gains in learning and reasoning processes (Mercer et al., 2004a), in addition to an ability to more effectively participate in problem solving tasks (Mercer et al., 1999).

**Problem-solving as an epistemic process**

In experiencing the uncertainty of epistemic processes, students potentially developed more robust problem-solving skills. Students’ complex pathways of emergent understanding is also consistent with the non-linear approaches identified in Kapur’s (2010) study of productive failure. Kapur (2010) highlighted a generative instructional strategy that involved enabling students to generate their own ideas, representations, and methods to solve complex problems before providing them with canonical structures. In his quasi-experimental design comparing two groups of Grade 7 mathematics students, the group that received
delayed canonical scaffolds (i.e., the productive failure group) were ultimately better able to apply these methods to solve novel problems. As the productive failure group was solving a complex group-based problem, students engaged in circular dialogue, generating a range of possible ideas and methods to solve the problem. By the time they were provided with the scaffolds, Kapur (2010) posited they had developed a better understanding of the affordances of the canonical representations and methods for problem solving. Students could better understand why their incorrect attempts were ineffective and demonstrated persistence in problem solving. In comparing these two groups, the group that was initially provided with the scaffolds were able to engage in static knowledge transfer, where they were able to apply their knowledge to similar contexts; whereas the treatment group developed generative knowledge transfer and were able to apply their knowledge to more novel situations and persist with the task even if they did not succeed.

In my study, students engaged in similar inefficient dialogic processes, developing representations on a needs basis to solve problems (e.g., spontaneous use of the carton to develop their hypothesis, generation of a data table to interpret the results from the dataloggers), as well as developing their own methods for addressing their inquiry questions. Despite not having a clear hypothesis and being challenged with contradictory data, students persisted with the task and developed a high quality report. Though students in my study received scaffolding in the modules leading up to the final task and in the task itself, according to Kapur (2010), engaging more directly in these complex processes would have developed generative knowledge transfer abilities to apply their problem-solving skills to novel situations.
If scientific discovery processes are to be understood as an adaptive dance between human and material agency, an inquiry task must provide the conditions for these epistemic experiences. In this study, the students had an authentic experience of scientific inquiry, developed a plausible explanation, and achieved a positive learning gain. Comparing students’ experience of the task with Pickering’s (1993, 1995) mangle provided insights into how these pathways of emergent understanding are reflective of scientific practice. Following Kapur’s (2010) productive failure analysis, allowing students to address complex tasks with minimal scaffolding could potentially support generative knowledge transfer. Though the process took more time than a single-class practical investigation, the task provided a generative example of an activity allowing students to engage more directly in authentic epistemic processes while still being manageable in the classroom context (Manz, 2015).

8.2.2 Summary of epistemic engagement in classrooms

The summative task was scaffolded within the unit as a digitally enhanced practical investigation and provided an authentic inquiry experience and assessment of students’ conceptual knowledge. Pickering’s mangle points to the interplay of agency, resistance, and accommodation in scientific practice and indicated how students’ complex conceptual progression in this task was an authentic reflection of scientific discovery processes. Similarly, Kapur’s analyses suggested that allowing students to engage in extended and complex problem-solving tasks has the potential to support generative knowledge transfer. Together, these insights indicate complex collaborative reasoning processes utilising multiple modes for interactions and material exploration, reflective of authentic inquiry processes.
My Chapter 6 analysis also identified design suggestions including embedded prompts and opportunities for ongoing representation construction in multiple modes to support reflections throughout the inquiry. These reflections would scaffold and highlight informal and formal reasoning processes as a legitimate part of the science knowledge discovery process, in addition to linking students’ observations with their representational accounts to support conceptual learning.

8.3 Patterns of Conceptual and Representational Development (RQ3)

The class completion of most of the activities along with the summative task indicated general engagement with the unit. Evidence from the case-level analysis included students’ multimodal responses, collaborative dialogue, refinement of their ideas, and application of their conceptual knowledge in the summative task. Combined, students’ learning in relation to the variety of classroom processes and their responses in the VSRI provided a more nuanced view of their complex learning journey. Overall, my findings indicated that while many prior conceptions were persistent, and the learning pathways were complex, there was growth. I argue that the patterns indicated the complexity of students’ learning pathways and were closely linked to the representational resources and contexts provided in the modules. To begin, I present key findings from Chapters 5 and 7, linking students’ learning pathways in the conceptual modules with multimodal meaning-making processes.

The case group’s most robust learning was associated with Modules 5 and 6, which included the use of diagnostic and cross-modal formative assessment, cross-modal activities, and representational challenges. These activities enabled students to show and translate their ideas across multiple modes and to transfer
their knowledge to different contexts. Both modules began with multimodal diagnostic assessment activities. The diagnostic text-based MCQs for energy transfer (see Activity 5.1) and cross-modal translations for conduction provided insights into students’ prior ideas (see Figures 5.13), and indicated many alternative conceptions (e.g., lack of particle movement in solids). Though students’ responses were not formally addressed, the processes of cross-modal translation in coordination with canonical resources supported a gradual uptake of scientific ideas.

For example, in Module 5, students proceeded with their first particle-level representational challenge (see Activity 5.2), followed by their first role-play (see Activity 5.3). Then, they experienced an EGR-SGR interplay, where they viewed an animation on particle motion then drew diagrams (see Activity 5.4). As a final activity, students applied their ideas to a multimodal representational challenge with text-based and open-ended questions (see Activity 5.5). In explaining her understanding of particle motion, Ina indicated that particles in solids were stationary (Activity 5.1); she demonstrated particle connectedness with no movement in her initial representations, but an ability to relate representations (Activity 5.2). In the role-play, she again did not show particle movement (Activity 5.3); but after the EGR-SGR interplay, she was able to draw particle movement through her own symbolic conventions, which she applied to the final activity. Ina also applied new terminology from the second purpose-made video. Figure 7.11 illustrates the multimodal ensemble of representations Ina used to explore energy transfer (e.g., textual, visual, actional) and their representational forms (e.g., written text, drawings, role-plays). The sequencing and sum of the modes were associated with her developing a gradual
and generative understanding of the concept and is consistent with the role of multiple representations for conceptual learning (Lemke, 1998b; Waldrip et al., 2013b).

My findings were therefore consistent with socio-semiotic multimodal theoretical accounts of the role of multimodal meaning-making resources to support learning. Semiosis is the process of relating objects to physical and symbolic representations (e.g., artefacts, 3D models, symbols) to make meaning or interpret phenomena (Prain & Tytler, 2012). The possibilities for semiosis are thus contingent on the range of representations, tools, and modes available in a learning environment and their meaning-making potential (Kress, 2010), as indicated in Module 5. In short, to support learning, there is a need to build students’ representational resources (Tytler & Prain, 2010). Further, the design of and practices used within a learning environment (e.g., laboratory, learning sequences) affects students’ ability to construct knowledge using these semiotic tools in a manner that emulates the disciplinary practices of science (e.g., inquiry, communal understanding). Within the context of RCA, these epistemic practices are provided through an iterative process of developing and refining SGRs through reflection and negotiation toward consensus understanding as a core disciplinary practice (Prain & Tytler, 2013; Tytler et al., 2006).

From a semiotic perspective, each mode offers the potential of a “productive constraint” in focusing students’ attention and deciding how best to express their ideas (Tytler & Prain, 2013b, p. 1024). The modal affordance for the drawings (Activities 5.2, 5.4, 5.5) required students to respond to different visual-spatial demands of each of the challenges (Ainsworth et al., 2011), along with deciding how to depict, distinguish, and relate representations (diSessa, 2004;
Kozma & Russell, 2005). The cross-modal translation from diagrams to role-play required students to make decisions about how to embody two dimensional ideas and relate ideas such as particle connectedness and motion, supporting a higher level of conceptual and representational understanding (Kozma & Russell, 2005). Ina’s pathway demonstrated a progression in depicting movement in particles, relating representations, and developing conventions. In assessing the progression of her RC, she demonstrated an ability to represent submicroscopic processes (i.e., Level 3), relate meaning between textual and visual forms (i.e., Level 4), and communicate an awareness of the form and function of the actional mode (i.e., Level 5).

While many of these features (e.g., role-plays, diagrams) were included in Module 6 (Conduction), there were fewer opportunities for cross-modal translations. Ina had challenges in applying her ideas about particle movement to other contexts. The first two activities were impromptu additions to the lesson sequence and provided formative cross-modal SGR translations from role-plays to annotated drawings (see Figure 7.12). The actional mode of the role-plays in both modules demonstrated students’ awareness of the form and function of representations, indicating a high level of representational competence (i.e., Level 5), in addition to enlisting embodied perspectives on learning (Ibrahim-Didi, Hackling, Ramseger, & Sherriff, 2017). These were the only cross-modal translations for this module. The remaining activities involved EGR-SGR interplay (see Activity 6.1), which required only text-based responses. Though these tasks provided an opportunity for students to reflect on their learning as an important part of their conceptual change (Vosniadou, 2008), they did not engage in multimodal explanatory accounts. Thus, students missed an opportunity to
translate their ideas across modes before resolving them into written forms. The final summative activity involved three MCQs where the case group scored below the class average (see Appendix B). While students maintained their ideas of particle motion throughout this module, the exclusion of representational challenges and open-ended multimodal responses limited their opportunities to experience cross-modal translations. This likely resulted in their limited ability to transfer ideas to other contexts, indicating the highly contextual nature of conceptual learning (Tytler & Prain, 2013a).

There were additional limitations in both modules related to formative processes. For example, though students’ responses for the Activity 5.1 quiz were automatically assessed through the STILE application, their responses were not addressed and did not inform the delivery of the module. This was also the case with the impromptu cross-modal activities in Module 6. As a result, the teacher missed an opportunity to assess students’ prior knowledge and adapt the learning sequence to meet students’ needs, which are important formative processes in RCA (Waldrip et al., 2010; Tytler et al., 2013b).

Similarly, the lack of explicit teacher-directed negotiation around their SGRs resulted in the teacher missing further opportunities for formative assessment through questioning and linking representations to guide students’ conceptual and representational development. As a result, students had limited experience with epistemic practices central to RCA (Tytler et al., 2013a; Tytler, Murcia, Hsiung, & Ramseger, 2017). The lack of scaffolding through evaluative processes indicates a need for additional supports to ensure teachers manage these aspects of RCA and to ensure such opportunities are accounted for within a digital delivery.
In addition to students’ responses throughout the modules, the interviews with the case group also presented insights into their learning. During the conduction module, students recognised the affordances of different representational forms as they compared role-plays and diagrams, indicating a high level of RC. Their elaborations on their post-test diagrams during the VSRI demonstrated a more complex range of conceptual understandings and uptake of terminology and conventions. Their elaborations were consistent with findings concerning the notion that concepts are contextually situated (Tytler, 1998), suggesting limitations to the over-reliance of pen and paper tests in assessing students’ learning.

Finally, the summative task provided an intensive practical context for students to apply their conceptual knowledge from Modules 5 and 6, which were more directly related to their inquiry questions. Though their collaborative explanatory accounts followed gradual and sometimes inconsistent progress, by the end of the task, they applied their ideas providing evidence of their claim, and demonstrated engagement in reasoning processes through their ability to use representations to explore, construct, and justify their claims (Tytler et al., 2013c).

The sequencing and provision of representational resources to support semiosis in Modules 5 and 6, combined with an opportunity to apply knowledge in the authentic context of the summative task likely influenced students’ overall improved and consistent conceptual and representational understanding of energy transfer and conduction. These generative experiences contrasted to those with Modules 7 and 8. Modules 7 and 8 were associated with more limited learning gains indicated by students’ responses to the tasks, the post-test, and the interviews. These modules were characterised by an introduction to the concept
through EGR-videos with no activities to elicit students’ prior knowledge, no cross-modal translations, and more limited opportunities for students to construct representations. Though Module 7 did not feature any representational challenges, it did have the only post-activity mapping task, which elicited a generative response by the students. While Module 8 did include a representational challenge, it was more text-based with limited multimodal interactions (see Figures 5.25 and 5.26). An additional issue with Module 8 was the exclusion of Activities 8.4 and 8.5 (see Section 4.1), resulting in students’ limited engagement with content and multimodal activities. Students’ perception of Module 8 was they had not “done much on radiation” and that it was not as visual, suggestive that they were aware of their limited interactions in this module. The related questions on the pre- and post-tests were arguably too complex for this unit, and resulted in inconsistent responses by the case group (see Table 7.6). In the interviews, all three students indicated some understanding of the trapping of heat in the atmosphere, but had difficulties in expressing their ideas through their annotated representations.

In summary, the patterns in the modules indicated the complexity of students’ learning pathways. While the pre- and post-tests indicated significant though limited learning gains, they did not indicate the processes of conceptual change (diSessa, 2006). Conceptual change was a gradual process and was associated with classroom activities involving cross-modal re-representations including representational challenges, and the meaningful application of knowledge to relevant contexts. Students’ learning involved making choices in constructing and communicating their ideas through a variety of modes and media (Prain & Tytler, 2013). Students received varying levels of guidance through
instruction and resources: with strong support for some tasks (e.g., using dataloggers, the summative task) and less support for others (e.g., negotiating SGRs). Limitations in formative assessment processes along with the poorly timed use of EGR resources likely impacted students’ opportunities to engage more deeply in meaning-making processes, resulting in inconsistencies with conceptual and representational development. My findings indicated the possibilities for semiosis were thus contingent on the range, coordination, and timing of representational resources in a learning environment and their meaning-making potential. These findings were consistent with multimodal theory (Kress, 2010) and distributed cognition (Hollan et al., 2000; Tenenberg & Knobelsdorff, 2014), indicating a greater complexity for digital learning environments. These patterns have implications for the design of learning sequences, the scaffolding of activities and representational resources, and the need for supports for formative processes. These ideas are addressed in RQ4.

8.3.1 The complexity of learning

My findings indicate that students’ conceptual learning was gradual and variable across contexts. Far from experiencing the dramatic uptake of canonical knowledge described in classical conceptual change (see Posner et al., 1982), students’ learning processes were more reflective of the complex and multifaceted nature of learning. This is consistent with the views expressed in contemporary learning sciences and science education literature (Duit & Treagust, 2012; Taber, 2011).

Following socio-semiotic theory, students’ learning gains were closely associated with the timely use of representational resources to support semiotic processes (Kress, 2010). Following distributive cognitive theory, students’
learning was linked to broader context, which encompassed the disciplinary tools and practices, including the social interactions Hollan et al., 2000; Tenenberg & Knobelsdorff, 2014). Students demonstrated gradual but positive learning gains associated with the carefully sequenced interactions across multimodal representations in different contexts in Modules 5 and 6, including an extended practical investigation where students applied these concepts. Students’ learning was less consistent in sequences when the concepts involved a more textual focus and less opportunity for engagement with multimodal SGRs, as in Modules 7 and 8. Students’ ability to translate their learning was variable across contexts (e.g., Module 6 MCQs), indicating a lack of consistency in their conceptual interpretation of phenomena (Tytler, 1998). Students’ overall journey was consistent with the gradual and challenging process of conceptual change (see diSessa, 2006; Tytler, 1998; Vosniadou, 2008). While students’ test responses indicated a broad understanding of their potential learning gains, their learning journey in this DLE exemplified the complexities of and strategies required to support more robust conceptual change. This calls into question the value of single test responses, which provide only a narrow view of students learning capabilities and a limited engagement with the disciplinary practices of science (Tytler & Prain, 2013a).

8.3.2 Assessing complex learning processes

To understand my students’ complex learning journey, I drew from a broad evidence-base: I assessed and compared their pre- and post-test results; assessed their SGRs and written responses across the unit and created a secondary analysis across their learning journey through the conceptual modules in association with aspects of the classroom processes; analysed their learning
associated with the summative task including the final report; observed students’ interactions in class and through the video record; and integrated students’ interview responses. My analysis was focused on both the learning processes and outcomes and suggests a stronger connection between the two (Duit & Treagust, 2012; Tytler & Prain, 2013a). That is, my assessment of students’ learning did not rely on a single right or wrong answer (see diSessa, 2006), but was to be understood as a complex process related to context. My methods supported this holistic assessment based on multiple responses, including evidence of how students constructed and used representations (Tytler & Prain, 2013a). Other researchers working in this area relied on assessing students’ learning primarily through qualitative accounts (see Hubber et al., 2010; Tytler et al., 2009; Waldrip et al., 2013b), with some using comparative pre- and post-tests (see McDermott & Hand, 2013; Tytler et al., 2013b).

Tytler et al. (2009) used detailed descriptions of students’ learning processes based on observations, interviews, and video records, as students engaged in discussions and interacted with multimodal representations throughout a unit. Similarly, Hubber et al. (2010) used a broad base of evidence around teacher judgements, anecdotes, and observations, in addition to an analysis of the students’ interviews. Waldrip et al. (2013b) observed students’ reasoning processes as they were creating and critiquing multimodal representations (e.g., drawings, 3D models). They also based their assessment on follow-up interviews, where students provided conceptual explanations of different scenarios as evidence of their retention in learning.

Other studies expanded assessment methods to include more quantitative measures for comparative purposes. The pre- and post-test strategy that most
closely resembled the one used in my study was the Year 8 astronomy instrument described by Tytler et al. (2013b). In addition to interviews, these researchers used the same nine-item MCQ test based on alternative conceptions in astronomy (see Kalkan & Kioglu, 2007). Tytler et al. (2013b) were then able to determine the normalised gain index for each item, calculate the gain for each of the participating classes, and compare their results with the other study.

A similar comparative approach was used by McDermott and Hand (2013) in reporting learning gains through multimodal writing-to-learn tasks in secondary chemistry. All students completed a standardised baseline science competency test along with a baseline writing sample. The competency task was based on an instrument developed by other researchers and consisted of twenty-one multiple choice questions covering a variety of science concepts found in national and international science instruments (i.e., NAEP and TIMSS). McDermott and Hand (2013) also used a rubric they developed to determine how well students embedded multiple modes of representations within text. The cross-case analyses showed treatment classes outperformed control classes in both tests. The combined use of closed-ended items and open-ended responses enabled a broad comparison of students’ learning gains while allowing the researchers to measure critical aspects of students’ responses in natural classroom settings. Each of these studies provides examples of holistic assessments of students’ learning, integrating multiple qualitative and sometimes quantitative methods.

My analysis involved a more structured assessment of the open-ended questions in the pre- and post-test using two different rubrics. The use of rubrics provided a more consistent and transparent assessment approach while indicating further challenges in assessing SGRs (see following section). The design of the
closed-ended MCQs in my study indicated a potential for comparative methods in conjunction with a more holistic assessment of students’ complex learning interactions. Embedding test-items that relate to other studies (Tytler et al., 2013b) or national and international tests (McDermott & Hand, 2013) present a viable way to compare learning changes more broadly and may be a practical solution in supplementing traditional assessment processes with more innovative pedagogies. Similarly, the use of small-scale comparative studies with control and treatment groups (McDermott & Hand, 2013) would be a potential next step for research in exploring representation-focused innovations in natural settings, leading to further refinement of the approach, information about implementation, and the potential scaling of this approach.

8.3.3 Assessment of SGRs

The pre- and post-tests in my study presented assessment challenges. While the MCQs were close-ended questions with answers linked to the misconception literature (AAAS, 2018), the open-ended questions had no equivalent answer key. The literature provided possible solutions, resulting in the development of two different rubrics to assess students’ conceptual understanding and ability to represent their ideas. Following Michalchik et al. (2008), I developed a conceptually-based assessment criteria for each of the three questions, guided by the content provided in STILE (see Table 7.4). Following Hilton and Nichols (2011), I modified Kozma and Russell’s (2005) framework on representational competence suitable for secondary students (see Table 7.5). This highlighted the challenge of using SGRs to assess students conceptual learning and indicated tensions in the literature around the relationship between students’ conceptual and representational understanding.
Representation-focused approaches embed formative assessment in the pedagogy through the negotiation and refinement of ideas (Prain, Tytler, Hubber, & Waldrip, 2013). This process provides insight into students’ ideas across multimodal representations for subsequent planning and adaptation of instruction, including the timely introduction of canonical ideas. Therefore, in comparison to the closed-ended MCQs, the open-ended responses were central to indicating change in students’ conceptual understanding through RCA. The construction and use of multimodal representations in a variety of contexts provide a more holistic conceptual account of phenomena and is more consistent with contemporary views of learning (Tytler et al., 2009).

The complexity of this assessment process is explained by diSessa (2004), who stated that judging the adequacy of representations is difficult as there is no single ideal representation, and representations are only understood in relation to the task and not directly comparable to EGRs which are designed for a different purpose; additionally, judging their effectiveness should be clear and unambiguous. Additional difficulties arise in assessing SGRs in isolation, given that no single representation can convey meaning fully (Lemke, 1998c; Waldrip et al., 2013b; Tytler & Prain, 2010). The students need to explore, communicate, and make links across representations (Kozma & Russell, 2005). Moreover, the ability to relate representations as a meaning-making practice requires appropriate tasks (Tytler et al., 2007; Tytler & Prain, 2010). As diSessa (2006) indicated, judging representations is both complex and context dependent.

Waldrip et al. (2010) pointed to the potential of diSessa’s (2004) MRC criteria to assess the adequacy of SGRs when they developed their IF-SO framework for planning and delivery of RCA. Although the details on applying
assessment practices remained very broad, they suggested that representations should to address a specific need, make particular claims, provide clear and sufficient information, and be comprehensive, in addition to being judged by their effectiveness in achieving these purposes. The researchers indicated that some of these features would need to be taught explicitly.

Sellings (2018) developed an SGR-assessment rubric based on diSessa’s (2004) competencies to assess a post-practical investigation activity in a Year 10 chemistry class. He followed the process developed by Nitz and Tippett (2012), where students’ initial responses were used to identify the criteria most suited to the task. He then sequenced the appropriate criteria to a four-stage rubric (i.e., high, medium, low, not shown) to assess students’ conceptual understanding: fidelity, systematicity, autonomy, conventionality, alignment. Though the rubric was used to assist the teacher in understanding how effective her pre-investigation explanation was (i.e., formative), it demonstrated its potential as a broader assessment tool.

In my study, I applied Kozma and Russell’s framework (2005) because it was based on the practices of scientists, thus more closely emulated epistemic processes. However, I simplified the framework to better suit my research participants. The need for more formal assessment practices for SGRs raises the question of how conceptual understanding is linked to students’ ability to generate representations (McDermott, 2016).

8.3.4 The relationship between conceptual and representational understanding

In my study, students’ conceptual understanding and representational competence in their pre- and post-test responses indicated a broad though sometimes inconsistent relationship across the items (see Table 7.6). The most
consistent patterns of growth were linked to conduction (i.e. Q8), where the case
group showed a coordinated improvement in both areas. For Ina, these gains were
consistent with her learning pathway in the energy transfer module (see Figure
7.11), and slightly less so with the conduction module (see Figure 7.12), where
the questions involved more text-based responses. Inconsistent patterns of
learning in the case group were linked to Q9 and Q10 concerning convection and
the greenhouse (see Table 7.6). While Clara showed only a slight improvement in
convection, Ina’s and Megan’s conceptual understanding seemed to be inversely
correlated with their ability to represent. Ina’s learning pathway for convection
(see Figure 7.13) also indicated an inconsistent pattern of growth, though her final
mapping response (Figure 5.21) suggested a positive link between her
understanding and ability to represent her ideas. In Q10, Megan’s responses
demonstrated a decreased RC while Clara’s demonstrated a decrease in
conceptual understanding. Ina’s responses suggested a small but more consistent
progression. Her pathways indicate a less robust understanding (see Figure 7.14),
though the questions in this module were more limited. These inconsistencies
might be attributed to the lack of teacher-led formative processes throughout the
unit, limiting students’ growth as a response to the provided online resources. In
addition, there were fewer opportunities for students to respond through open-
ended SGRs in Modules 7 and 8, and limited opportunities for them to represent
and thus provide evidence of their potential abilities; that is, I simply might not
have had enough evidence on which to base these comparisons.

In comparing these patterns to the literature, questions arise regarding the
link between conceptual learning and representational competence and the
identified a link between students’ conceptual understanding and metarepresentational competence. Students’ *inscriptions* depicted increasingly varied and differentiated ideas coupled with explanations and increasing dimensionality (i.e., 2D, 3D), resulting in a “cascade of conceptual change” (p. 352). Sellings (2018) study involved a more structured assessment of this link, through a rubric based on diSessa’s (2004) competencies. The results corroborated diSessa’s (2004) study: that SGRs enabled teachers to determine students’ level of conceptual understanding. Students’ responses indicated those with higher levels of understanding constructed increasingly sophisticated representations.

However, diSessa (2004) indicated possible limitations with this idea. He suggested that the use of representations assists with students’ understanding or making sense of concepts, though were not necessarily reflective of their level of conceptual understanding. In addressing this potential relationship, diSessa (2004) noted that evidence for the *co-development* of representational and conceptual competence was also limited in the literature and additional research in this area is needed to explore this link.

**8.3.5 Summary of students’ complex learning journey**

My findings indicated that students’ conceptual learning was gradual and variable across contexts. Linking the details of students’ learning to the particularities of classroom processes and activities provided a more holistic reflection of their potential ability to engage in a range of multimodal activities as a disciplinary practice. Students’ learning journey was much more complex and contextual than indicated by the results of the post-tests, suggesting the need for a more holistic evidence-base of students’ learning that better reflects the processes
involved in the multimodal nature of scientific conceptual understanding (Yore & Hand, 2010).

My results are consistent with the challenges identified in assessing students’ conceptual understanding through their representations (diSessa, 2006). With the embedded nature of formative practices in RCA, teacher-facilitated discussions around the form, function, and adequacy of SGRs, along with the timely introduction of canonical ideas, are meant to provide structured support for students’ conceptual and representational development. This ongoing formative assessment is arguably the most important assessment practice for representation-focused approaches. It links conceptual learning to knowledge construction processes. More broadly, my results indicated the need to assess the adequacy of current mainstream practices in science education (Waldrip, Hubber, & Prain, 2013a), particularly in development and assessment of multimodal knowledge construction processes. While researchers ostensibly have the resources to apply multiple rubrics and evidence for a robust accounting of summative learning, the practicalities of teaching and classroom assessment call for a more accessible approach. This implies the need for more research and development of summative tasks and assessment strategies in these classroom settings.

8.4 Implications for the Design of Digital Learning Sequences (RQ4)

The unit was designed based on the principles of RCA. This involved opportunities for students to share and explore their ideas, with gradual guidance toward scientific understanding as they construct, relate, and refine their multimodal SGRs through ongoing discussion and negotiation of ideas (see Tytler et al., 2013b); this process is particularly salient for the conceptually-focused modules and tasks. The provision of guidance and representational resources in
context is integral to supporting the semiotic and epistemic processes underpinning this approach (Tytler & Prain, 2010). My findings indicate students’ conceptual and representational development occurred gradually and was contingent upon their guided-experience involving multiple opportunities to generate, refine, and apply multimodal SGRs in different contexts. In addition, the sequencing of activities and representational resources along with the flexibility in using them, impacted students’ learning, indicating potential challenges and implications in the digital sequencing of RCA.

Students in the study showed overall engagement in the tasks presented in the modules and an ability to generate a variety of multimodal SGRs (see Chapter 5). A closer analysis revealed that some sequences were more strongly supportive of semiotic and epistemic engagement (e.g., Module 5 energy transfer) than others (e.g., Module 8 radiation). Further, the omission of formative processes (e.g., understanding students’ prior knowledge, negotiation of SGRs) and issues in the timing of EGR resources, likely impacted students’ learning potential. To explore this, I summarise the patterns of students’ learning presented in the previous section and highlight the generative features, their affordances in supporting semiotic (e.g., multimodal meaning-making processes) and epistemic (e.g., ongoing evaluation and refinement through disciplinary practices) processes consistent with RCA, and the implications of their digital sequencing in the modules.

Across the modules, the lack of teacher-facilitated discussion around SGRs and students’ responses to formative assessments likely had the most impact on students’ learning. Similarly, there was a lack of scaffolding to support these processes within the online platform itself. Evidence from my study
indicated cross-modal representations, the timely introduction of EGR resources, and the meaningful application of knowledge to relevant contexts supported multimodal meaning-making processes in science. Students had more limited engagement in these processes when: EGR resources were presented prior to eliciting students’ ideas, when questions involved more text-based responses, and where there were limited opportunities to generate and apply multimodal representations to solve problems and engage in hands-on tasks. The following sections address the inter-related roles of discussions, eliciting students’ ideas, cross-modal engagement, and the timing of EGR resources in digital lesson sequences, in supporting students’ more robust conceptual understanding.

8.4.1 The role of discussion around SGRs

Although the DLE involved a large amount of face-to-face dialogic interaction (see Chapter 4), a closer analysis indicated limited discussion and assessment around SGRs. This was evident in the lack of whole-class discussions around the students’ diagnostic assessments (e.g., pre-tests, Activity 5.1), missing opportunities to identify and address possible misconceptions. It was also evident around students’ SGRs (e.g., role-plays, drawings), missing opportunities for students to clarify form, function, and adequacy, and guide them toward a scientific understanding. Further, students also missed out on negotiating their ideas as a more authentic engagement in the knowledge construction processes of science. This facilitated dialogue involving feedback and development of communal understanding, is central to non-cloud-based representation-focused classroom processes (see Hubber, 2014; Lehrer & Schauble, 2006; Tytler et al., 2009).
These processes have their basis in socio-cultural and socio-semiotic perspectives. Socio-cultural perspectives advocate a central role for dialogue in learning in science classrooms, as students engage in discussions around joint problems and tasks, constructing shared understandings in specific cultural contexts. These perspectives emphasise the influence of cultural practices on language and thought (Vygotsky, 1962, 1978). Similarly, socio-semiotic perspectives foreground the role of cultural resources (i.e., modes, practices) for meaning making through social interactions, emphasising the cultural or disciplinary influence of different modes and how they are used and interpreted (Kress, 2010). Together, they indicate the social role of learning the languages and processes of science through classroom-based resources and practices supporting the teaching and learning of science. Students’ limited engagement in these classroom epistemic processes affected their construction of meaning, impacting their conceptual and representational development.

In contrast to transmissive delivery of content, the teacher-facilitated dialogic interactions in RCA establish and develop students’ ideas toward canonical understanding, using SGRs as prompts to drive discussion (Hubber et al., 2010). The learning sequences thus need to involve an interplay between dialogue and SGRs (Tytler et al., 2013a), which emulates the communal knowledge building practices in science. Further, the SGR-EGR interplay consists of the ongoing negotiation of purpose, form, function, and adequacy of SGRs towards peer and canonical consensus. Through this process, the teacher can assess students’ initial and developing ideas, adapt the activities and level of guidance to support conceptual understanding, and facilitate students’ experience of knowledge construction processes. In response, students gradually incorporate
canonical ideas as they develop their conceptual and representational competence. In conjunction with feedback, students need guidance in negotiating conceptual understanding through SGRs within groups and as part of whole-class discussions (Lehrer et al., 2000; Waldrip et al., 2010).

Given the central role for these formative processes around SGRs, the consequences associated with the omission of these interactions impacted students’ conceptual learning, their ability to represent ideas, and their engagement in communal knowledge building practices. The research suggests these discussions require specific scaffolding by the teacher (Tytler et al., 2007) through questioning and prompts (Hackling, Murcia, & Ibrahim-Didi, 2013; Waldrip et al., 2013b). The integration of the online learning platform likely placed additional demands on the teacher, suggesting the need for additional supports for a digital RCA. These include training for teachers to lead the process of unit design and to learn to incorporate these digital features across face-to-face and online domains. Additional supports could be provided within the platform itself.

The platform-based support could include the development and integration of digital scaffolds or prompts into the learning sequences to more explicitly promote these crucial dialogical interactions around SGRs. These could follow similar language to that proposed in the RCA resources, requiring students to elaborate on the form and function, purpose, and adequacy of their representations (Tytler et al., 2013b; Waldrip et al., 2010). Interactive discussions such as these also require the use of open and exploratory language, necessitating longer and more structured discourse around conceptual tasks, placing additional demands on both students and the teacher (Hubber et al., 2010). The development of possible
questions and examples of concept-specific interactions (e.g., videos, transcripts) could be embedded in the learning sequences or included as part of the online teacher resources. Both involve additional resources to be embedded into the online learning platform as part of the research-led design.

8.4.2 Eliciting students’ prior knowledge

Understanding and building on students’ conceptual ideas is the foundation upon which learning occurs and is the basis for planning and adapting learning through RCA (Waldrip et al., 2010; Tytler et al., 2013b). I distinguish diagnostic activities as the initial activity at the beginning of the unit or module, from the ongoing formative assessment embedded in the pedagogy as the communal negotiation and refinement of ideas (Prain et al., 2013).

The first module of the unit presented a pre-test to identify students’ prior conceptual understanding about energy transfer along with two open-ended tasks involving word clouds and mind maps. Modules 2 and 5 included prior activities in the form of closed-ended MCQs, and Module 6 included an impromptu multimodal translation activity with role-plays and drawings. Though students received instant feedback on the MCQs, their results were not addressed to discuss common understandings and issues, or used to plan and adapt subsequent pedagogy around students’ response. Consequently, it is likely that students’ conceptual learning processes relied on their own ability to identify issues and integrate relevant canonical information, without targeted guidance by the teacher. The intention of RCA is not only to provide individualised and co-constructed canonical content to the students, but to emulate the process of knowledge construction.
Given that many of these opportunities were already scaffolded within the online platform, the more purposeful use of these features included an expanded use of the automated instant feedback application to better support these diagnostic processes. The unit was already designed such that the teachers’ online resource section mapped the pre-test questions with the relevant module, providing a broad conceptual focus to modules. Within each of the modules, there is potential to further map diagnostic assessments with the respective activities, in addition to providing additional information and resources to support teacher-led delivery. Within the capabilities of STILE, an application was available through the automated instant feedback to the Activity 6.1 quiz (see Q3-5), providing specific information related to students’ given responses. An expanded integration of automated feedback in STILE would involve more input into the design of MCQs, placing additional demands on unit planning. However, these experiences would provide more opportunities for students to learn through their assessments and more in-depth information about their conceptions to inform subsequent instruction.

### 8.4.3 Representing across modes

As I have argued, the DLE provided flexibility and expanded access to semiotic resources. From a semiotic perspective, learning involves students’ capacity to translate across and coordinate multimodal representations. This representational re-description is a key aspect of learning and demonstrating understanding through representation-focused approaches (Lemke, 1998c; Lehrer & Schauble, 2006; Waldrip et al., 2010).

In my study, students experienced cross-modal interactions in Module 5 through multiple modes and representational forms, two of which were sequenced
as open-ended multimodal representational challenges. Module 6 included an impromptu cross-modal diagnostic assessment, and Module 7 featured the only mapping activity. The results indicated strong overall learning gains attributed to Module 5 along with the more consistent transfer of learning to different contexts, included the subsequent module. While Module 6 had fewer such interactions, these concepts were linked to the summative task which provided spontaneous opportunities for representational re-description across multiple modes. The cross-modal interactions were more limited in the following two modules. Module 7 included the only post-investigation mapping activity in the unit, where students linked their conceptual ideas of convection currents with their observations of the rocket. Though Module 8 included a representational challenge, it involved a more superficial coordination of representations with an emphasis on the textual mode.

Opportunities for students to represent across modes supports deeper conceptual learning through the iterative and transformative processes of constructing, selecting, and refining semiotic resources for meaning making (Lemke, 1998b). Because each mode offers different affordances, students need to make decisions about which mode to use and for what purpose based on the semiotic resources provided (Kress, 2010). Each time a student represents and re-represents ideas across modes, decisions to accommodate the productive constraints for each mode are required (Lehrer & Schauble, 2006; Tytler & Prain, 2013a) in addition to understanding how these modal ensembles interact (Bezemer & Kress, 2016). Cross-modal engagement is linked to improved conceptual understanding (diSessa, 2004; Tytler et al, 2013b; Waldrip et al., 2006) and integral to the development of students’ representational competence.
(diSessa, 2004; Kozma & Russell, 2005). This also applies to cross-modal engagement related to practical investigations, where students’ links to theory tend to be more limited (Abrahams & Millar, 2008; Hofstein & Lunetta, 2004). Two-way mapping involves students’ connecting their experiences and observations with representations to support conceptual learning during hands-on activities and demonstrations (Tytler et al., 2013b).

Thus, the provision of diverse representational resources with cross-modal interactions are critical for the design of generative learning sequences. I have argued that the DLE expanded semiotic resources and provided the flexibility for students to engage in meaning-making processes using both digital and non-digital media; in response, students constructed a variety of SGRs across modes. The design of learning sequences should thus include the sequencing of digital and non-digital activities including representational challenges, to support an extended interaction with concepts in different contexts. In addition, the inclusion of two-way mapping tasks with all hands-on activities would support students’ conceptual development. While the SGRs in this unit were mostly drawings, the impact of the two role-plays suggested the inclusion of this actional mode would positively influence learning.

*The role of actional modes*

Students’ responses to the role-plays indicated their experience was positive, memorable, and helpful (see Section 7.2.3). Only Modules 5 and 6 included role-plays (e.g., states of matter, energy transfer through conductors and insulators). They presented specific visuo-spatial affordances for learning that also provided information about students’ ideas. The use of the actional/gestural mode has presented distinct modal affordances in representation-focused
approaches (Tytler et al., 2007; Hubber et al., 2010). From a semiotic perspective, this mode requires students to translate across verbal and actional modes, supporting a deeper conceptual understanding. The link between verbal and actional modes is central to an embodied cognition that relates or grounds actions to thoughts, providing a more direct and possibly more powerful link to abstract ideas (Goldin-Meadow & Beilock, 2010). Role-plays also function as analogies, supporting informal reasoning processes (Klein, 2006). While the use of gestures and role-plays in RCA has been shown to be generative (Tytler et al., 2006; Tytler et al., 2013b), much of the research has tended toward students’ drawings. More recent research has indicated the potential of the embodied mode for learning through RCA (Ibrahim-Didi et al., 2017). The impact of role-plays in this unit suggests a purposeful role for these SGRs in learning sequences. While these would largely take place outside the digital domain, students’ reflections of their role-plays could take place online, as they did in Activity 5.3. The DLE would also support students’ uploading an image or video of their role-play, with the potential for online comparative purposes.

In summary, providing opportunities for students to represent and re-represent across modes supports students’ meaning-making processes. The DLE in this study expanded the representational resources to enable these processes to take place using both digital and non-digital media. The final aspect I identified that influenced students’ learning was the timing of canonical resources.

**8.4.4 Timing of EGRs within the lesson sequence**

Compared to Modules 7 and 8, the learning gains in Modules 5 and 6 suggest that the placement of EGR resources played an important role in students’ uptake of canonical ideas. In Modules 5 and 6, the resources were introduced after
formative multimodal representational tasks. Students’ responses indicated a gradual uptake of ideas (e.g., particle motion) and an ability to apply their ideas in other contexts (e.g., summative task). In contrast, the other two modules began with the purpose-made videos, and Module 8 included a large amount of canonical content in the initial activities. Students’ responses indicated immediate uptake of canonical information (e.g., arrow conventions for convection currents) and the superficial transmission of ideas (e.g., Activities 8.2, 8.3).

The timing of canonical information (e.g., textbooks, teachers’ explanations, images, internet sites) has been identified as a key challenge in teaching and learning through representation-focused approaches. It requires a balance between allowing students to explore and represent their own ideas about phenomena, and providing them with canonical information and guidance to represent their ideas and make links (diSessa, 2004). To support this interaction, the teacher needs to make a judgement about how much variation to allow outside canonical conventions to support students’ creative exploration, along with the amount of guidance needed to support a more robust canonical understanding (Waldrip, Prain, & Carolan, 2006). Though the teacher was not active in guiding these processes, the placement of these resources within the digital learning sequences had implications for students’ learning. In Modules 5 and 6, students explored their ideas through multimodal SGRs prior to being presented with the EGR resources (e.g., drawings, role-plays). Whereas in Modules 7 and 8, the initial teacher-led, whole-class verbal exploration of students’ prior ideas preceded the provision of canonical resources. This limited opportunities for cross-modal representations. The contrast in learning gains suggests more
consideration is needed for the generative sequencing of activities and resources to support gradual and more robust learning progressions.

The impact of timing is consistent with the literature in non-cloud-based classrooms. EGR timing was attributed to inconsistent learning gains in a comparative case study with primary students (Lehrer et al., 2000). A review of the lesson and students’ responses indicated the timing of canonical information impacted students’ ability to develop conceptual understanding. The researchers claimed that if an EGR was presented too early, students became more concerned with external features, syntax, or procedure, instead of the meaning; if presented too late, students may not have understood the principles well enough to translate them to another activity. My results were consistent with the former, where students’ immediate uptake of canonical information was indicated throughout Modules 7 and 8, with limited evidence of their conceptual understanding. Lehrer et al. (2000) emphasised the time required for students to develop personally meaningful learning through their active construction, revising, evaluating, and problem solving as an investment in developing deeper conceptual understanding compared to transmissive approaches.

While the role of the teacher is integral in the timely introduction of canonical information, in my study, this information was largely provided through the digital learning sequence. The implications for design are that the activities need to be adaptable. In general, formative SGR activities should occur early in the learning sequences. Teachers would then refine the planned interactions in response to students individual and collective understanding as described in more detail below.
8.4.5 Resources for designing learning sequences

The findings in my study indicate important considerations for the design of generative learning sequences for online learning platforms. Sequencing should begin with multimodal prior-knowledge activities (see Module 6). Subsequent activities need to allow students opportunities for cross-modal translations, with more in-depth representational challenges (see Module 5), two-way mapping activities (see Module 7), and include actional modes where possible (see Modules 5, 6). Activities that elicit students’ prior ideas and allow them to explore in different contexts should precede EGR resources. In enacting the learning sequences, the teacher’s role would thus involve facilitating ongoing formative practices, adapting the activities, and matching the timing of resources in accordance with students’ responses.

Embedding activities and resources in a digital learning sequence implies fixed pathways, however, the teacher’s orchestration of activities and the students’ agency in selecting representational resources for meaning making supports adaptations and variations in learning pathways. In my study, the STILE platform was an accessible authoring tool that accommodated impromptu changes. This included changes outside the platform, as demonstrated with the conduction role-plays and drawings (see Module 6), and with the convection currents demonstration (see Module 7). The platform also enables the teacher to show or hide activities or modules, allowing the use of pre-planned supplementary materials, though this function was not used.

In relating these generative design features with the literature, my findings are consistent with some of the key frameworks and planning resources but with specific adaptations for a digital delivery. The IF-SO framework was designed to
assist planning design and delivery of learning sequences in non-cloud-based classrooms (Waldrip et al., 2010). The framework identifies the central role in orienting the teaching around key concepts and provides broad guidance around the sequencing of representational challenges and tasks. It emphasises the need for students to re-represent their ideas, the timely coordination of EGRs, and the role of teacher-led negotiation around SGRs. Building on this, the pedagogical Principles for RCA (Tytler et al., 2013b) elaborate and re-organise the key features presented in the IF-SO framework, focusing on teaching sequences, discussion, mapping, and assessment. The Principles feature discussion more prominently, and a stronger emphasis on representational challenges. Where the Principles provide more detail on the key features of RCA, the IF-SO framework provides more guidance on how to plan the learning sequences. Other resources provide additional assistance in the planning of representation-focused lessons and units.

The 5E inquiry-based model was developed as a teacher-specific resource to scaffold learning sequences (Bybee, Taylor, Gardner, Van Scotter, Powell, Westbrook, & Landes, 2006). This teaching approach involves five learning phases (i.e., Engage, Explore, Explain, Elaborate, Evaluate) to scaffold lessons and units, each with a particular teaching and assessment focus. The early phases call for activities that enable students to share their prior understanding. In the Explain phase, students are guided towards scientific explanations. Students then demonstrate their understanding in different contexts and evaluation takes place throughout the sequence. All of these phases were consistent with the unit design in my study, particularly with the first four phases.
The application of the 5Es Model with an inquiry-based representational approach has been taken up by the Australian *Primary Connections* science program, which includes curriculum and professional development resources (Primary Connections, 2018). Their approach has been considered effective in supporting teachers’ planning and students’ improved learning outcomes (Hackling & Prain, 2005). In supporting the increased use of representations, the approach has emphasised teacher-student negotiation as students explored and refined their conceptual ideas across multimodal representations (Hackling & Prain, 2005). The use of 5Es to scaffold representation-focused approaches was also indicated in an evaporation sequence (Tytler et al., 2006) and an astronomy unit (Hackling et al., 2013), both aimed toward the primary levels and indicating positive learning outcomes. While the *Primary Connections* model provided a practical framework from which to build representation-focused sequences, it did not elaborate on the nuanced nature of the SGR-EGR interplay.

To support these interactions, Kenny and Cirkony (2017) integrated the IF-SO model with the 5Es to support planning and delivery for representations. They identified the tension in planning was with the practical need to create linear sequences and units yet be adaptive to the students’ needs. Salient features of this 5Es-representational model include identifying key concepts for the unit, and within each phase: describing teacher and student interactions, assessment approaches, and strategies around representational practices. Though presented in sequence, the researchers indicated that in practice, there would be overlap in the first three phases as students’ ideas are elicited, assessed, and developed.

In summary, these frameworks and guiding principles provide support for the planning of key processes in representation-focused approaches, along with
strategies for planning activities and units. In addition to these resources, which were developed around non-cloud-based classrooms, the findings in my study emphasise specific features and practices important for the design of generative learning sequences for online platforms, demonstrating specific digital affordances which are explored below.

8.4.6 Designing digital learning sequences

While the enactment of the cloud-based unit took place in a regular classroom setting, the digital learning environment emphasised generative practices of RCA consistent with the literature, in addition to presenting unique digital affordances.

While the generative practices of RCA have been identified, refined, and established in non-cloud-based classrooms, their impact on students’ learning in this DLE indicated additional possibilities and demands for planning learning sequences. My study emphasised the role of eliciting students’ prior ideas, providing multiple opportunities for cross-modal translations, consideration of the timing of EGR resources, and teacher-facilitated discussions around SGRs. My findings also indicated the inclusion of the following to support socio-semiotic processes: both closed- and open-ended multimodal activities, multimodal representational challenges, role-plays, post-investigation mapping activities, and purpose-made videos.

Adapting RCA to the digital mode presented a number of affordances and considerations through this interactive cloud-based platform to support generative practices. The platform expanded flexibility and access to multimodal representational activities and resources to support socio-semiotic processes. Specific use of applications supported whole-class interactions, provided
customised feedback to students’ responses, and allowed students to generate
digital and multimodal representations and more expansive text-based responses.
The platform was an accessible authoring tool that supported face-to-face small
and large group activities, in addition to incorporating select internet-based
resources. The design and delivery of this cloud-based unit also indicated the need
for additional supports for key formative practices. This included the need for
embedded prompts and resources to facilitate discussion and negotiation of SGRs,
and the consideration of the timing of activities and EGR resources. Table 8.1
relates the generative practices of RCA and the digital affordances of this cloud-
based unit in supporting generative learning processes.
Table 8.1
Designing Learning Sequences to Support Representation-Focused Approaches

<table>
<thead>
<tr>
<th>Generative Practices</th>
<th>Digital Affordances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial assessment activities need to involve the elicitation of students’ prior ideas through both closed- and open-ended questions and multimodal activities based around key concepts and common misconceptions.</td>
<td>The flexibility of an interactive online platform accommodates face-to-face and digital interactions across multiple media, thus supporting multimodal diagnostic activities while accommodating student agency. The live poll supported whole-class discussion around students’ responses; the automated instant feedback application provided more elaborate feedback on students’ responses.</td>
</tr>
<tr>
<td>Opportunities for students to express, re-represent and refine their ideas through cross-modal representations, including multimodal representational challenges, role-plays, and mapping activities to support hands-on experiences.</td>
<td>The DLE expanded access to digital and non-digital representational resources. The online platform provided flexibility to access either domain. The interactive online canvas allowed students to construct and coordinate representations of equivalent quality to their hand-drawn SGRs. The infinitely expanding ruled pad allowed for less restriction of text-based responses.</td>
</tr>
<tr>
<td>The timing of the EGR resources involves SGR-EGR interplay. The teacher guides students toward gradual canonical understanding in coordination with their SGRs.</td>
<td>The careful placement of EGR resources is required to support students’ productive engagement with their SGRs. This typically would occur after initial elicitation of students’ ideas and in coordination with the cross-modal engagement. The authoring capability allows for impromptu changes within the platform.</td>
</tr>
<tr>
<td>Consideration of the adaptive interaction with students’ initial ideas, their cross-modal SGRs, and the timing of EGR resources.</td>
<td>The platform is an accessible authoring tool that accommodates impromptu changes of online and face-to-face activities. It also has features to show or hide activities and modules as needed.</td>
</tr>
<tr>
<td>Emphasis of teacher-facilitated discussion and feedback around SGRs to assist individual, group, and whole-class interactions.</td>
<td>Additional questions and prompts within the tasks are needed to support both teachers and students as they engage with the activities.</td>
</tr>
<tr>
<td>Group and whole-class discussion and collaboration.</td>
<td>The integration of outside resources (Google Docs) supported an elaborate collaborative task. The purposeful integration of Class Discussion into the modules could support additional platform-based collaboration.</td>
</tr>
<tr>
<td>Purpose-made videos and resources linking static and dynamic representations, and macroscopic and submicroscopic features in everyday contexts.</td>
<td>Embedding these representational resources in the learning sequence requires the consideration of timing by the teacher in accordance with students’ response.</td>
</tr>
<tr>
<td>Classroom delivery supportive of the teacher orchestration of learning sequences.</td>
<td>The cloud-based platform supports the teacher orchestration of the learning sequence across face-to-face and online domains. The platform also has the potential for a fully blended delivery of RCA. As a BLE, it has the potential to provide more flexibility, agency, and support accessibility, differentiation and online collaboration, along with more dedicated class time for formative processes.</td>
</tr>
</tbody>
</table>
8.4.7 Summary of implications for designing digital learning sequences

Students’ responses indicated both generative and problematic features in the design and delivery of this digitally-based unit, which impacted key interactions to support semiotic and epistemic processes. My results indicated the importance of students representing across modes, the careful sequencing of these processes within a digital platform, and importantly, the teacher’s orchestration and adaptation of activities informed by ongoing discussion, assessment, and feedback as students construct and negotiate their SGRs. Affordances through the digital sequencing of this interactive pedagogy support and expand a range of generative practices, but also place additional demands on both the teacher and students in navigating a complex pedagogy associated with an interactive online learning platform, along with the use of additional tools in this digital learning environment.

8.5 Engaging Students in Learning Science

In summary, I respond to the overall research focus, “to investigate how a digital learning environment designed with an inquiry-based RCA engages students in learning science.” In this final section, I focus on the wider issues of student engagement that were presented in the first two chapters of this thesis (see Sections 1.1 and 2.1).

In a post unit interview the teacher, Sophia, noticed the high level of student engagement with this physics unit, observing:

They are engaged, they are trying to keep up with the work, they are trying to understand, they put lots of time into their drawings, they tried to improve on them, they tried to add extra information, they engaged in
dialogue with the people at their table to say: What did you think? What are you putting there? Why are you doing that?

Sophia went on to comment that: “I’m not sure I’ve ever really experienced it [the level of engagement] teaching physics to all girls”. She then identified specific features that supported students’ engagement, including the context of sustainable energy, the range of activities and resources in STILE, the novelty of working in STILE, and using a special project book to record their ideas. She noticed students enjoyed using the datalogger and “had that very proud look on their face like they were serious scientists”. Sophia also commented on collaborative report writing task, noting that the entire class submitted it on time, and their writing indicated their collaborative voices. The findings in my study corroborate these observations, indicating a high degree of whole-class participation in the tasks, student-to-student dialogue throughout the unit, and the collaborative reasoning demonstrated by the case group in the inquiry task.

The high degree of engagement with the unit contrasts with the general lack of interest and participation in secondary physics reported in the literature, particularly with girls (Labudde, Herzog, Neuenschwander, Enrico, & Gerber, 2000; Lyons & Quinn, 2010). Though larger studies looking at science achievement suggest that girls and boys have similar learning outcomes in science (OECD, 2016; Quinn & Cooc, 2015), girls tend to have a less positive attitude toward the subject (OECD, 2016) with a declining interest beginning in earlier grades (Labudde et al., 2000; UNESCO, 2017). Apart from the culturally-based association with gender on girls’ participation in physics (UNESCO, 2017) classroom practices have also impacted attitudes and participation. The transition from transmissive or teacher-led approaches toward more student-centred
approaches, engaging students’ prior knowledge and ideas, relating physics to everyday contexts, and increased collaboration have been shown to improve girls’ attitude and engagement in physics (Labudde et al., 2000). Further, the engagement of students’ creativity through the active sense-making practices of representation-focused approaches is thought to attract students who might not otherwise be interested in the science (diSessa & Sherin, 2000). These approaches align with many features of the unit in this study.

Results of an intervention study where teachers implemented different instructional strategies, demonstrated a significant improvement in girls’ attitudes towards physics (Labudde et al., 2000). The study involved 25 teachers teaching the first 40 lessons in a required secondary course to 600 students across 31 classes. The initial survey showed significant gender related differences in experience, self-confidence, and interest in physics, along with similar spatial and language abilities. The results indicated that girls’ attitudes in the intervention classes showed significant improvement. The most effective strategies for the girls’ learning involved: the integration of individual preconceptions where students had a chance to share their own ideas; opportunities to relate everyday language to scientific language and everyday physics to people and society; and opportunities for discussion and cooperation. In my study, all of these strategies were consistent with RCA and enacted in the unit. While the measure of students’ attitudes was not central in my research question, the degree of students’ engagement in the unit suggested this approach to teaching energy transfer may help improve students’ attitudes toward physics and influence their continued engagement in the subject.
More broadly, Lemke (2004) indicated the more gendered nature of the *hard sciences* results in a narrow view of scientific practice. He suggested that more direct engagement in the creative and intuitive processes inherent in scientific inquiry, the emphasis on the artistic and aesthetic modes of representations, along with increased collaboration would better support females to identify with the practices of science and contribute to a more contemporary view of scientific literacy. These features are consistent with representation-focused approaches, which have indicated motivational and attitudinal gains (Lehrer et al., 2000; Tytler et al., 2009).

My findings have demonstrated promising student engagement and learning outcomes in physics. The generative features of the DLE supported students’ interactions with disciplinary-based semiotic processes, along with genuine epistemic engagement through inquiry-based tasks. Improvements to formative assessment processes and the design and delivery of learning sequences would support more consistent experiences in learning through representation-focused approaches.
Chapter 9. Conclusion

While research into the generative delivery of RCA undertaken in non-digital environments indicates deeper conceptual learning and engagement in science (Tytler et al., 2018), my research extends this work to the productive integration of digital technologies in classrooms (OECD, 2015a). My findings demonstrate the generative affordances of digital modes of delivery, and provide considerations for the design of digital learning sequences incorporating RCA, and insights into the nature of inquiry tasks through a Distributed Cognitive (DCog) perspective.

In the previous chapter, I addressed the research focus and questions in relation to the literature, summarised my key findings, and identified implications. In this chapter, I clarify the conclusions that have emerged from my detailed analyses in Chapters 4–7 by outlining new contributions to the literature arising from my study, and elaborate on implications and possibilities for future research. I conclude with a reflection on my study.

9.1 Contributions to the Literature

My investigation involved the delivery of a physics unit using an interactive pedagogy through a cloud-based platform integrating multiple technologies. The combination of digital delivery with RCA supported students’ engagement in discipline-specific knowledge construction processes, which resulted in significant, though inconsistent, learning gains. My thesis presented evidence of the viability of digital delivery of an RCA, in which specifically designed and sequenced digital resources and activities supported socio-semiotic focused learning processes, along with epistemic processes of scientific inquiry.
9.1.1 The affordances of a DLE in supporting RCA

My findings indicated that the DLE was not only compatible with RCA, but extended flexibility and access to multimodal semiotic resources to support students’ meaning-making processes. The digital environment opened up construction, coordination, and evaluation possibilities through disciplinary knowledge construction processes. In comparison with non-cloud-based RCA approaches (see Hubber et al., 2010; Tytler et al., 2007; Waldrip et al., 2013b), the digital delivery supported more varied student-generated representations (SGRs) and more individualised learning pathways.

The online learning platform provided affordances to support inquiry-based and semiotic learning processes. The platform was an accessible authoring tool for the teacher-led orchestration of learning sequences; it enabled the integration of face-to-face and online activities through individual and social interactions as a cohesive unit. The platform also enabled students’ flexibility and agency through their choice of representational resources (e.g., tools, modes), activities, and expression of ideas through more open-ended responses (e.g., interactive canvas, infinitely expanded ruled pad for unlimited text-based responses, multimedia uploading tool). These interactive applications illustrated the possibilities for digital platforms beyond the storage and delivery of content (see Richards & Dede, 2012; Richards & Walters, 2012) and indicated a viable digital discipline-specific inquiry approach (see Bidarra & Rusman, 2017; Longo, 2016). For assessment, the platform expanded traditional multiple choice assessment practices (e.g., live poll, automated instant feedback). Further enhancements would include the purposeful use of the collaboration tool (i.e., class discussion) to support productive online interactions. The development of
aggregation tools would support the collaborative assessment of open-ended responses.

The purpose-made videos also provided unique affordances. The design features for presenting and relating multiple representations reflected the best practices indicated in the research (see Ainsworth, 2006, 2008; Renkl & Scheiter, 2017), resulting in generative representation-focused resources. This suggests the need for the development of further video resources following these design guidelines.

9.1.2 Considerations for design of digital RCA learning sequences

The application of distributed cognitive theory demonstrated the impact of context on learning (Tenenberg & Knobelsdorf, 2014) and the role of mediating tools in supporting disciplinary practices of knowledge construction (Hollan et al., 2000). By linking products with practices to identify factors that affected students’ conceptual and representational development, I illustrated a new way to explore these patterns in context (see Duit & Treagust, 2012; Tytler & Prain, 2013a) as an ensemble of students’ representational experiences.

The findings indicated students’ conceptual learning was gradual and varied across the representational resources and contexts provided in the learning environment; consistent with the literature on conceptual learning (Tytler, 1998; Tytler & Prain, 2010; Vosniadou, 2008) as well as socio-semiotic theory identifying the multimodal nature of science (Kress, 2010; Lemke, 2004), as translated to a digital environment. My methods of assessing students’ representations indicated the complexities of assessing static representations (see diSessa, 2004, 2006) and the need for more holistic assessment practices (see Yore & Hand, 2010).
DCog also provided insights into the effective design of learning sequences, beyond what could be gained from just reviewing students’ output (Halverson & Clifford, 2006). While many of the features of the sequence under study were similar to non-cloud-based RCA classrooms, my findings revealed specific experiences that were not consistently embedded into the design of the digital unit. These included: the lack of initial multimodal activities to elicit students’ prior knowledge; few opportunities for multiple cross-modal translations including representational challenges, two-way mapping, and actional modes of representation; and issues with the timing of resources used to introduce canonical information. My findings also emphasised the importance of the role of the teacher in RCA: for facilitating discussions around students’ representations; undertaking other ongoing formative practices to guide students through the activities; and adapting the timely introduction of resources in response to students’ learning. The centrality of the teacher in these interactions suggested the need for additional training and embedded digital supports across the sequence for ongoing guidance.

9.1.3 Insights from a distributed cognitive perspective on inquiry tasks

For the summative inquiry task, students’ engagement in epistemic processes of scientific inquiry and their gradual but generative application of conceptual knowledge led to a high-quality final report. The DCog framework provided insight into this complex inquiry task by relating specific tools (e.g., representations, digital and non-digital tools) and reasoning processes, more so than could have been understood through just an analysis of students’ final report (see Halverson & Clifford, 2006). Initially, the case group formed informal and tentative ideas which were associated with non-digital and transient
representations (e.g., gestures, model manipulations). As they refined their ideas, they began to translate their representations across different modes, prompted by the datalogger (e.g., data tables). Eventually, their more formal and resolved ideas were associated with the digital written word through a collaborative online tool (i.e., Google Docs). Throughout the task, the students engaged in emergent and collaborative reasoning processes employing a variety of representational resources in response to the task.

My analysis indicated that students’ seemingly chaotic development and refinement of ideas during this task were more closely aligned with authentic scientific inquiry (see Latour, 1999; Pickering, 1993, 1995) and potentially supported generative knowledge transfer processes (see Kapur, 2010). My findings demonstrate these stages of exploration and refinement as legitimate experiences of classroom investigations and are consistent with the literature (see Abrahams & Millar, 2008; Duschl & Grandy, 2013). The generative attributes of this guided inquiry task included: a meaningful context, collaborative participation, constrained provision of materials, time-limits, provision of digital collaborative tools, and group-based reports.

These findings are also consistent with the use of representation-focused approaches to more closely align with epistemic practices of science (Tytler & Prain, 2013b). From a socio-semiotic perspective, students’ spontaneous use of representations and ability to link material and symbolic representations indicated a high level of representational competence (Kozma & Russell, 2005). Further, their explanatory accounts emerged as they refined their ideas across multiple modes, indicating the importance of cross-modal translations in supporting
conceptual learning processes during investigations, as is the case with authentic inquiry processes

9.2 Implications and Future Research

The significance of my research lies in its contribution to extending RCA to digital learning environments and managing the socio-semiotics processes within this setting. My findings have direct implications for the ARC digital inquiry project by increasing understanding of the affordances of the digital technologies in supporting this interactive pedagogical approach through the students’ perspective. My findings are also of interest to educators and organisations looking for strategies to shift science teaching and learning towards processes that more closely emulate scientific practices and support the productive integration of digital technology in learning environments.

Implications of my findings are thus organised into four areas: further considerations in designing digital RCA learning sequences in science; the use and design of online learning platforms; considerations for curriculum and assessment; and the potential for engaging all students in science and STEM. These implications, along with suggestions for future research are discussed in the following four sections.

9.2.1 Additional considerations in designing digital RCA learning sequences

In addition to the considerations outlined in Section 9.1, I highlight those regarding inquiry tasks and for teachers. The generative attributes of the guided inquiry task required time and disciplinary-specific tools to support students’ gradual exploration, development, and refinement of ideas. Embedding prompts and questions that call for multimodal responses would support these informal and formal reasoning processes as a legitimate part of science knowledge.
discovery processes. In addition, there needs to be opportunities provided for guided and/or spontaneous cross-modal translations, where students realise the need for representations to solve problems and make claims. Further, in conjunction with the final report, a post-practical investigation mapping activity where students link their observations with specific representational accounts would support deeper conceptual learning.

My findings indicated the design and delivery of RCA placed demands on the teacher, similar to experiences reported in non-cloud-based classrooms (Tytler et al., 2013b). The DLE placed additional demands by combining a challenging pedagogy within an interactive online learning platform, along with the need to navigate between multiple and digital tools. Earlier, I indicated the need for instructional supports for a digital RCA (e.g., training, embedded resources, prompts) to support ongoing formative practices. My analysis of transcripts and videos of discussions and negotiation with students around SGRs enabled insight into the strategies involved in this dynamic process.

Developing these additional supports for teachers could involve extending the researcher-led design team to include a broader inter-disciplinary membership (e.g., researchers from the learning sciences, learning platform software technicians, out-of-field teachers, graphic artists) to ensure the efficacy and accessibility of the next generation of this approach. These supports are found in the designs of some of the more elaborate online learning platforms (see Linn et al., 2003; Quintana et al., 2004).

9.2.2. Use and design of online learning platforms

With the lack of consistent learning gains in ICT-rich settings (OECD, 2015a), there is a need for continued research into the rapidly evolving online
learning platforms to ensure the generative integration of these approaches. While
I have already argued that the STILE platform provided key affordances to
support the generative delivery of RCA, the more purposeful application of the
existing collaboration tool and the development of an aggregation tool to collate
SGRs would expand both online and face-to-face interactions including
assessment practices. Because this platform has illustrated the generative capacity
to integrate resources from the internet (e.g., Google Docs), the addition of digital animations and simulation programs would further enhance students’ conceptual learning as part of a cohesive design. Examples such as the Chemsketch program enabled students to construct 2D and 3D molecular models, supporting a deeper conceptual understanding of chemical bonding through dynamic representational approaches (see Michalchik et al., 2008).

I have also indicated the potential of web-based adaptive learning platforms that provide automated and more customised, elaborate, and multimodal feedback to students’ responses, but involve more complex software design and training. Digital RCA could inform the disciplinary-based design of learning sequences to support students’ knowledge construction. The Web-based Inquiry Science Environment (WISE) platform currently allows teachers to embed prompts (e.g., hints) and resources (e.g., simulations, drawing tools) within the learning sequence (Slotta & Linn, 2009). She and Liao’s (2010) web-based adaptive learning system featured conceptually-based questions that triggered the ongoing provision of customised multimedia information and resources that guided students toward conceptual change. Digital RCA would provide a more active representational-approach to these designs.
The limitation of assessing open-ended responses in STILE are addressed by current cyber-learning tools. These tools have evolved beyond providing feedback to fixed single responses and are now capable of scoring essays and drawings (Linn et al., 2014) with similar and sometimes improved efficacy to that of teachers (Gerard, Matuk, McElhaney, & Linn, 2015). The digital prompts and scoring rubrics are initially designed by the teacher and then automatically assigned by computer according to students’ responses. These tools are capable of learning from human-scored responses to refine their guidance. For example, AutoTutor analysed students’ explanations for misconceptions and provided specific prompts to elicit better information (Linn et al., 2014). The integration of these cyber-learning tools with digital RCA would support the larger scale assessment of student-generated representations, providing more individualised feedback and assisting the teacher in identifying broad trends in the classrooms. These adaptive learning systems and cyber-learning tools also support more comprehensive and refined experiences for fully blended approaches.

Future research is needed for the dynamically growing area of online learning platforms in supporting RCA. Firstly, to continue to investigate the digital delivery of other representation-focused units in STILE, and similarly accessible platforms based on the evidence-based practices identified in this study. The delivery would take place in classrooms and in fully-blended learning environments. Similarly, the integration of RCA in other platforms warrants further investigation, particularly in fully blended settings. Finally, the creation of a fully digital RCA-informed design for a platform would warrant research in the development and delivery of online science units. Extended socio-cultural theories such as distributed cognition (Hutchins, 2010, 2014) are currently being
used to investigate human-computer interactions in context, integrating the intended and actual use of digital technology in the design to create more responsive technologies. Learning through multimodal representational resources implies the dual demand of learning the concepts and how to use and express them through different media, as interrelated processes (Hutchins, 1995; Lemke, 1998b). This coupling, from the perspective of students, offers insight into the design of tools, learning systems, and the task itself, consistent with the potential of DCog theory (Pea, 1993; Salomon, 1998; Tenenberg & Knobelsdorf, 2014; Zhang & Norman, 1994).

9.2.3. Considerations for curriculum and assessment

My findings indicate considerations for curriculum at both a classroom-based and policy level. RCA challenges and expands the notion of what a concept is, based on the multimodal nature of scientific concepts (Lemke, 2004; Taber, 2013). Thus, to understand science requires students to construct, coordinate, and interpret multiple modes of representation in context (Tytler et al., 2013b). At a policy level, science curriculum is presented exclusively as linguistic propositions (ACARA, 2018), leaving the disciplinary-based interpretation to teachers. This is not only challenging for science-trained teachers, but also for those who have little or no disciplinary-based understanding of science or science teaching (Hobbs, 2013). The combined demands of this approach within a digital setting implies an important role for inter-disciplinary collaboration for the design of activities, lesson sequences, and units.

My study has reinforced the centrality of representational work in conceptual learning, and hence underlines the importance of framing curriculum in representational terms. This applies to both policy and classroom-level
curriculum. Similarly, teacher-training methods and resources need to reflect the multimodal nature of scientific concepts along with appropriate methods and activities to support representation-focused approaches. These include activities where students construct and relate multiple representations to problem-solve. Further research is needed into the development of such activities and resources, including the role of the actional mode (e.g., gestures, role-play).

There are similar challenges with assessment practices. My findings indicated that the learning process was more complex than could be determined by single or text-based response items. Moreover, these more traditional methods of assessment does not reflect multimodal conceptual understanding or students’ ability to engage with the disciplinary practices of reasoning and problem-solving. My research has opened up possibilities for thinking of assessing student understanding as an ongoing process and implies a need for research into the development and efficacy of more holistic classroom-based assessment practices to support representation-focused approaches. This includes both formative and summative practices. My research has also demonstrated a complex relationship between conceptual and representational understandings. At a theoretical level, more research is needed to explore this link. This area of research would inform the design of practical resources and strategies for assessing SGRs in the classroom. For larger scale assessments, further research into the use of cyber-learning tools in assessing more open-ended responses would support more widespread use of representation-focused approaches. For research-based assessments, the strategy of embedding test items along with the use of comparative tests would enable the learning gains to be compared more broadly.
9.2.4. Considerations for student engagement in science and STEM

The high degree of student engagement in the active-knowledge construction activities throughout the unit and summative task suggests this digital approach is both effective and generative for engaging girls in science. The delivery of this unit followed classroom practices linked to improved student engagement: participation in active and creative representation-focused approaches (diSessa & Sherin, 2000); opportunities to relate everyday physics to people and society (Labudde et al., 2000), particularly through contemporary socio-scientific approaches (Besson & De Ambrosis, 2014); and opportunities for discussion and cooperation (Labudde et al., 2000). Further, these practices challenge traditional approaches to teaching science and may also appeal to Indigenous students, where their cultural views are sometimes perceived to be at odds with Western science (Freeman et al., 2015). Because RCA has students actively constructing and discussing, it should inherently be more culturally responsive than traditional authoritarian approaches (Moje & Hirschman, 2004) and open up perspectives of different representational traditions (Tytler & Prain, 2013a). Further research is needed on attitudes and engagement of under-represented groups learning science through RCA.

9.3 Methodological Reflections

While much of the representation-focused research has taken place in classrooms, mine was among the first to take place in a digital learning environment within a cloud-based unit. This resulted in a confluence of opportunities, complexities, and limitations.

My research was situated primarily in the qualitative research paradigm, but also included a quantitative analysis of students’ pre- and post-test responses.
Drawing on both paradigms afforded different insights into students’ experiences of this digital RCA approach through multiple theoretical perspectives (Denzin & Lincoln, 2013; Schwandt, 1998). Comparing students’ responses through multiple data generation methods (e.g., test results, drawings, interviews) contributed to the breadth and depth of my interpretations through the integration or crystallisation of these methods (Denzin & Lincoln, 2013). Importantly, these methods revealed much about the complex and contextual nature of learning that is often not reflected through a single method. Focusing on the students’ response also provided me with more information about their experiences in this DLE, resulting in insights about the representational resources, consistent with DCog theoretical approaches (Pea, 1993; Salomon, 1998; Tenenberg & Knobelsdorf, 2014).

As an ethnography, my role as a participant observer provided me with a more immersive experience of the DLE. However, I am aware that my presence, perceived as both a teacher and a researcher likely impacted students’ experiences of the unit to varying degrees, particularly when I took on specific instructional roles (e.g., instructing a lesson, demonstrating how to use the datalogger); this is consistent with the subjective nature of research (Denzin & Lincoln, 2013). As a case study based on a single group of students within a single classroom experience, my findings are not meant to be generalisable (Cohen et al., 2013); instead, they provide more in-depth insight into practices and possibilities of digital RCA. My findings led to insights into the digital affordances for RCA, along with new ways of thinking about the distributed nature of representational resources for meaning-making processes, consistent with the role of case studies (Denzin & Lincoln, 2011; Yin, 2014). Though the classroom-based setting
involved minor interruptions (e.g., teacher and student absence, other school-based activities reducing class-time), research in this naturalistic setting more directly connected theory to practice. The study provided evidence to inform the design and delivery of a digital RCA. It also resulted in context-based recommendations for the further development of resources to scale this innovation or deliver it through fully blended approaches (e.g., aggregation tools, cyber-learning tools). The consideration of design-based research would be appropriate for future studies focusing on the iterative development of unit design in context (Puntambeker, 2018).

Finally, videoing two groups made the research design more manageable, though a complete video record for all case groups for all lessons would have contributed to a more robust data set. In spite of this potential gap, the volume of data generated through the video record and the full data set required the need for data organisation and reduction. While this proved to be a time-consuming task, it also resulted in multiple viewings of the video record in coordination with multiple sources of data, supporting a more reliable interpretation of my data (Atkinson & Delamont, 2005). Indeed, the iterative and increasingly refined representations of my data were consistent with scientific meaning-making processes, as I gradually resolved the multimodal data into this written thesis (Latour, 1990).
References


Appendices

Appendix A. End of Unit Online Questionnaire.

We are interested in your experiences in using STILE. Please share your experiences below to help us improve the online learning opportunities. This survey will take around 15 minutes.

Overview

1. What you think were the key ideas of this unit?

2. How do you know that you learned these key ideas?

3. Describe the most effective activities you participated in that helped you learn. Rate the following activities from 1-5, with 1 being the least effective and 5 being the most effective. Indicate by typing an X in the box (i.e. talking with your partner, talking with your teacher, listening to your teacher's explanations, participating in whole-class discussions, drawing in your learning journal (project book), drawing in Paint, answering questions in STILE, watching video clips, making a presentation (e.g., PowerPoint), constructing a mind map, watching demonstrations (by teacher such as the potassium permangante demo for convection), doing the temperature prac, doing the sustainable housing prac, doing the pre- or post-test, other).

Notebooks and Technology

4. For each of these, explain how you used them for this unit, how they were helpful, how they were challenging, if they had any specific benefits for learning science, and if/how you used them at home: Laptop, STILE, Learning Journal.

5. List your top three software, apps or other programs you used in this science class (e.g., PowerPoint, Google Docs, Puppet Pals) and explain how they supported your learning.

6. Did you review or return to any activities or videos in STILE after you completed your assignments (i.e., to find more information). Please explain.

7. For some of the drawings/diagrams, you used your project book and you used the Paint app in STILE. Which was more helpful for your learning? Use the table below to describe the benefits and challenges of each.

Sustainable Housing Project

6. How did you decide on your groups’ inquiry question?

7. After you moved into your groups, how did you decide who does what?

8. How did your original hypothesis compare with your actual results?
9. Thinking back to your hypothesis, your choice of materials for your inquiry, and your results, which science ideas did you refer to most (e.g., energy, particle theory, conduction, convection, radiation). Please explain using the table below.

10. What were the benefits and challenges of using the dataloggers? Please explain.

11. When you learn something, what are the benefits and challenges of: working in groups, working by yourself, having a whole-class discussion.

Science Class
12. Think of your most memorable science class. Describe what you did. What made it memorable?

13. Describe your top three suggestions for improving this unit for the next class of Year 9 students.
### Appendix B. Students’ Responses to Activity 5.1.

<table>
<thead>
<tr>
<th>Questions and Concepts</th>
<th>Responses</th>
<th>True</th>
<th>False</th>
<th>IDU</th>
<th>NS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. When a substance freezes the temperature must always be less than 0°C. (Thermal Energy)</td>
<td>Class-level</td>
<td>81%</td>
<td>15%</td>
<td>0</td>
<td>4%</td>
</tr>
<tr>
<td>False*</td>
<td>Case-level</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I don’t understand</td>
<td>Ina</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not sure</td>
<td>Megan</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clara</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. It is possible to heat an object to +1000 °C but it is not possible to cool it -1000°C. (Temperature, Thermal Energy)</td>
<td>Class-level</td>
<td>42%</td>
<td>35%</td>
<td>0</td>
<td>23%</td>
</tr>
<tr>
<td>True</td>
<td>Case-level</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>False</td>
<td>Ina</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I don’t understand</td>
<td>Megan</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not Sure</td>
<td>Clara</td>
<td>False</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. When wax melts the molecules that make up the wax change from being hard and firm to being soft and ‘gooey’. (Particle Theory of Matter)</td>
<td>Class-level</td>
<td>58%</td>
<td>23%</td>
<td>11%</td>
<td>8%</td>
</tr>
<tr>
<td>True</td>
<td>Case-level</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>False</td>
<td>Ina</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I don’t understand</td>
<td>Megan</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not sure</td>
<td>Clara</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. A closed bottle with small amount of water at the bottom is left in the sun. After a while, when the water has evaporated, the mass of the bottle is now less than before. (Particle Theory of Matter)</td>
<td>Class-level</td>
<td>77%</td>
<td>15%</td>
<td>0</td>
<td>8%</td>
</tr>
<tr>
<td>True</td>
<td>Case-level</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>False</td>
<td>Ina</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I don’t understand</td>
<td>Megan</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not sure</td>
<td>Clara</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. The molecules inside liquids and gases are moving but in solids they are stationary. (Particle Theory of Matter)</td>
<td>Class-level</td>
<td>62%</td>
<td>38%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>True</td>
<td>Case-level</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>False</td>
<td>Ina</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I don’t understand</td>
<td>Megan</td>
<td>False</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not Sure</td>
<td>Clara</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. In the spaces between atoms of an object there is air. (Particle Theory of Matter)</td>
<td>Class-level</td>
<td>46%</td>
<td>23%</td>
<td>0</td>
<td>31%</td>
</tr>
<tr>
<td>True</td>
<td>Case-level</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>False</td>
<td>Ina</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I don’t understand</td>
<td>Megan</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not Sure</td>
<td>Clara</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. A pie that heats up in a gas-fired oven can be explained by air molecules in the oven colliding with pie molecules. (Energy Transfer, Particle Theory of Matter)</td>
<td>Class-level</td>
<td>73%</td>
<td>12%</td>
<td>0</td>
<td>15%</td>
</tr>
<tr>
<td>True</td>
<td>Case-level</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>False</td>
<td>Ina</td>
<td>False</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I don’t understand</td>
<td>Megan</td>
<td>False</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not Sure</td>
<td>Clara</td>
<td>True</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The correct answer is in boldface*
### Appendix C: Students’ Responses for Module 6 Activity 6.1.

<table>
<thead>
<tr>
<th>Questions and Concepts</th>
<th>Responses</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. A student is holding a cold piece of metal in her hand. While she is holding the piece of metal, her hand gets colder. Does the piece of metal get warmer? Why or why not? [Energy transfer, conduction]</td>
<td>Class-level</td>
<td>5%</td>
<td>65%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>Case-level</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ina</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Megan</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clara</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A. Yes, the piece of metal will get warmer because some thermal energy is transferred from the metal to the student’s hand.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B. Yes, the piece of metal will get warmer because some thermal energy is transferred from the student’s hand to the metal.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C. No, the piece of metal will stay at the same temperature because an equal amount of thermal energy is exchanged between the student’s hand and the metal.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D. No, the piece of metal will stay at the same temperature because thermal energy is not transferred between the student’s hand and the metal.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. A cook uses an iron frying pan to cook a meal. After cooking, he places the hot frying pan on the counter. After a while, the frying pan, the counter, and the air in the room will be at the same temperature. Why? [Energy transfer, conduction]</td>
<td>Class-level</td>
<td>25%</td>
<td>20%</td>
<td>40%</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>Case-level</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ina</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Megan</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clara</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A. Because thermal energy will be transferred from the frying pan to the counter and from the frying pan to the air.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B. Because coldness will be transferred from the counter to the frying pan and from the air to the frying pan.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C. Because thermal energy will be transferred from the frying pan to the counter and from the frying pan to the air, and coldness will be transferred from the counter to the frying pan and from the air to the frying pan.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D. Because thermal energy will be transferred from the frying pan to the air, but thermal energy will not be transferred from the frying pan to the counter.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Your little brother’s toys have been left outside all day in the Sun. As you collect the toys to them to bring them inside you find that the metal truck feels hotter than the plastic ball. Why is this? [Energy transfer, conduction]</td>
<td>Class-level</td>
<td>20%</td>
<td>70%</td>
<td>0</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>Case-level</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ina</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Megan</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clara</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A. The truck heated up more than the ball and so will transfer more thermal energy to your hand.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B. The truck and ball are the same temperature but the truck will transfer energy more quickly to your hand than the ball.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C. The truck and ball are the same temperature but the truck will transfer energy to your hand but the ball will not.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D. The truck has more thermal energy than the ball.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The correct answer is in boldface*