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AN EXPLORATORY CONSTRUCTIVIST GROUNDED THEORY STUDY: HOW SECONDARY SCHOOL SCIENCE TEACHERS INTERPRET STUDENTS' SCIENTIFIC MODELS THAT ARE COMPRISED OF DRAWING ACTIVITIES

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by

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Abstract

Extant literature lacks an explanation of the thought processes used by secondary school science teachers to interpret students' scientific models that are comprised of drawing activities. In this exploratory study, a constructivist grounded theory (CGT) was developed to generate an interpretive understanding. The CGT was generated from observations, interviews, and document analyses of five research participants consisting of secondary school science teachers from lower New York State. To generate a CGT, concepts, terms, assumptions, and definitions from selected theories—decolonizing methodologies theory (DMT), visual semiotic theory (VST), and cultural studies theory (CST)—collectively provided a fresh onto-epistemological lens for initially examining and bringing transparency to the invisible influences on the intangible thought processes of science teachers when they interpret students' scientific models. At the end of the study, a CGT was developed which is expressed as nine assertions, a diagrammatic display/axial coding paradigm, and an explanation consisting of found poetry developed from the research findings. Using reflective and reflexive analytical memos, this study revealed that the thoughts of secondary school science teachers consist of five themes: (1) direction or rules, (2) forms of communication, (3) creations (4) interpretation or understanding, and (5) problem-solving heuristics during students' struggle. In addition, the theory illustrated that in the context of lower New York State, science disciplinary culture works by crossing borders (Aikenhead & Elliott, 2010; Carter, 2011; New York State Education Department, 2019a; Rasheed, 2001, 2006; Snively & Corsiglia, 2001) between Western cultural thoughts and non-Western/Indigenous cultural thoughts. This study will benefit both stakeholders and scholars. For stakeholders, this study offers a substantive theory for understanding the assessment practices of science teachers. For scholars, this study provides a CGT that integrates theories/subdisciplines that are epistemologically distant/close and generates ongoing research. In particular, the theory provides scholars with findings that can be used to subsequently conduct a quantitative study, whereby a culturally sensitive survey instrument can be generated and validated.

Keywords: scientific models, constructivist grounded theory, visual semiotics, culture, decolonizing methodologies

List of Figures

Figure 1: *Constructivist and Constructionist Conceptions of Knowledge* 9

Figure 2: *Theoretical Model of Interpreting Drawing Activities Proficiency* 34

Figure 3: *Theoretical Framework Graphic* 43

Figure 4: *Model of Types of Semiotics* 46

Figure 5: *Conceptual Model of Signs* 47

Figure 6: *Conceptual Model of Polysemic Nature of Sign* 48

Figure 7: *Procedural Model of Research Design* 59

Figure 8: *Coding Style: In Vivo Codes to Theme* 68

Figure 9: *Model for Storyline Generation* 69

Figure 10: *Coding Techniques Used to Create the Codebook* 97

Figure 11: *Model of Hierarchical Clustering Technique* 104

Figure 12: *The Cycle of Enculturation* 112

Figure 13: *CGT Model of How Science Disciplinary Culture Works/Operates* 122

Figure 14: *The Continua of Science Teachers' Thought Processes* 126

Figure 15: *Ant on a Canoe* 141

List of Tables

Table 1: *Participants' Profile* 61

Table 2: *Codebook of Science Teachers' Thought Processes* 79

Table 3: *Declarative Statements Generated from Teacher#1* 100

Table 4: *A Zoom-In View of the Hierarchical Clustering Technique for Directions or Rules* .. 104

Table 5: *Constraints Imposed by Disciplinary Symbols* 109

Table 6: *Assertions Summarizing the Science Teachers' Thoughts* 119

List of Abbreviations

CGT	Constructivist Grounded Theory
CR-S	Culturally Responsive-Sustaining Education
CST	Cultural Studies Theory
DMT	Decolonizing Methodologies Theory
GT	Grounded Theory
MBA	Model-Based Assessment
MBI	Model-Based Instruction
NYS	New York State
NYSSLS	New York State Science Learning Standards
NYSMTP	New York State Master Teacher Program
NGSS	Next Generation Science Standards
n-W/ICT	non-Western/Indigenous Cultural Thought
STANYS	Science Teachers Association of New York State
VST	Visual Semiotic Theory
WCT	Western Cultural Thought
WEIRD	Western Educated Industrialized Rich Democratic

Contents

Acknowledgments ... iii

Abstract ... v

List of Figures ... vii

List of Tables ... viii

List of Abbreviations ... ix

CHAPTER 1: OVERVIEW ... 1

Situating the Study as a Constructivist Grounded Theory ... 7

Constructivist/Constructionist Worldview ... 8

My Approach to Culture ... 9

Using Constructivist/Constructionist to Challenge Positivism ... 11

Cultural Meaning ... 14

Power as a Consequence of Culture/Culture as a Consequence of Power ... 15

Cultural Context ... 18

Research Validity ... 22

Research Delimitations ... 24

Research Contribution and Significance ... 25

Organization of the Dissertation ... 26

CHAPTER 2: LITERATURE REVIEW ... 28

Instructional Best Practice for Drawing Activities ... 30

Static Drawing Activities Paired with Expository Text and an Illustration ... 31

Static Drawing Activities Paired With Expository Text Lacking an Illustration 32

Static Drawing Activities Paired with Animations.. 33

Dynamic Drawing Activities 34

Multiple Representations of Drawing Activities 35

Semiotic Organization of Drawings and Their Meaning 37

The Nature of Drawings... 37

Noteworthy Examples of Rules Involving Symbol Systems.. 39

Methodological Groundings.. 40

Developing My Theoretical/Conceptual Framework 42

Summary 51

CHAPTER 3: METHODOLOGY 53

Nature of Grounded Theory Methodology... 53

A Rationale for Selecting Constructivist Grounded Theory 54

Research Questions 58

Research Design.. 58

Participants 59

Data Collection Methods and Analysis 65

Establishing Trustworthiness 73

Ethical Considerations... 75

Limitations 77

CHAPTER 4: FINDINGS 78

Methodological Decisions During Codebook Development and Management........................ 79

Transcription Protocol 94

Use of Sensitizing Concepts as A Priori Data 95

Pilot Study 95

My Approach to Coding 96

Integrating the Literature 98

Tentative Theorizing.. 99

Data Reduction Protocol... 102

Twists and Turns in the Changing Research Ecosystem.. 107

Example 1: Curious Researcher Surprised by the Missing Data....................................... 107

Example 2: Excited to be a Practitioner-Researcher and Participant Researcher 113

Example 3: The Reflective Researcher Changing Perspective on the Journey................... 116

The Thought Processes of Secondary School Science Teachers 118

The Role of Culture in the Science Teachers' Thought Processes 121

Science Disciplinary Culture Crosses Border 124

Summary of the Findings 126

CHAPTER 5: CONCLUSION 128

Theoretical Contributions.. 128

Implications for Stakeholders 130

Science Teachers 130

District Leaders.. 133

New York State Policymakers.. 134

Future Researchers 135

Future CGT Scholars.. 137

Limitations of the Study.. 138

Personal Reflection 140

References.. 142

Appendix A: Survey Questions 165

Appendix B: Observation Protocol.. 166

Appendix C: Document Analysis Protocol with Visuals.. 167

Appendix D: Document Analysis Protocol without Visuals 169

Appendix E: Interview Protocol 171

An Exploratory Constructivist Grounded Theory Study: How Secondary School Science Teachers Interpret Students' Scientific Models that are Comprised of Drawing Activities

CHAPTER 1: OVERVIEW

The purpose of this study is to develop a constructivist grounded theory (CGT) that explains the thought processes used by secondary school science teachers to interpret students' scientific models that are comprised of drawing activities. In the research project, the primary focus will be on static drawing activities, that is, activities that manually construct intentional marks on a receptive surface using a system of rules aided by a drawing instrument (Lyon, 2020).

Before I proceed to contextualize my study, I will first introduce what scientific models signify/mean[1] in this study since in the literature, there is no universal definition used among advocates─philosophers of science and science educators (Frigg & Hartmann, 2020; Halloun, 2006). The term "scientific model" has dual roles—as a process and as a product—in the Next Generation Science Standards (NGSS) curriculum (Passmore et al., 2017; Wu & Rau, 2019). As a product, scientific models are visual representations[2] (Gilbert et al., 2000; Gilbert, 1991;

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[1] Here and throughout the body of this work, there are instances where the plurality of language is deliberately used to highlight the subjective epistemology that is used to interpret and express linguistic conventions.

[2] In the literature reviewed, scientific models are also perceived as a set of ideas (Passmore et al., 2017), current understandings (National Research Council, 2012), purposeful descriptions (Wang et al., 2014), explanatory stories (Gilbert et al., 2000; Wang et al., 2014), analogies (Harrison & Treagust; 2000; Lehrer & Schauble, 2010), complements of theories, preliminary theories, and subsidiaries of theories (Frigg & Hartmann, 2020). However, in the project, I have chosen to concentrate on the attribute of visual representation since the interest of this thesis is on static drawings—a visual product.

Treagust et al., 2002; Windschitl et al., 2018) that are simplifications of systems or phenomena[3] (Gilbert et al., 2000; Gilbert, 1991; Schwarz et al., 2009, as cited in Hokayem & Schwarz, 2014; Potochnik et al., 2018). When systems and phenomena are abstract/invisible, multiple models are utilized to highlight the various attributes of the target (Harrison & Treagust, 2000; Treagust et al., 2002). In science classrooms, scientific models serve as memory, explanatory, and learning tools (Harrison & Treagust, 2000; Tversky, 2011). Ranging in complexity, conventional representations[4] include "drawings, diagrams, flow charts,[5] equations, graphs, computer simulations, physical replica[/scale models,]" (Windschitl et al., 2018, p. 115) and analogies[6] (Frigg & Hartmann, 2006; Frigg & Hartmann, 2020; Harrison & Coll, 2008; Harrison & Treagust, 2000; Lehrer & Schauble, 2010).[7] Importantly, scientific models consist of only

[3] Scientific models are also constructed for ideas, events, processes, and thought experiments (Gilbert et al., 2000; Treagust et al., 2002). However, since the NGSS and New York State Science Learning Standards (NYSSLS) curricula focus on systems and phenomena, I chose to also adopt this approach for the dissertation since my target audience will be members of this population. In addition, an *event*—"a time-limited segment of the behaviour [sic] of one or more entities in a system" (Gilbert et al., 2000, p. 11), a *process*—"one or more events within a system which have a distinctive outcome" (Gilbert et al., 2000, p. 11), and *thought experiment*—"[a] group of processes known as a 'scientific experiment' carried out entirely within the mind as an idea" (Gilbert et al., 2000, p. 11) are associated with systems.

[4] Despite being simplified visual representations, I have deliberately excluded exemplars—model organisms (Potochnik et al., 2018)—because they are not nonbiological human constructions as is the case of the other examples.

[5] Here, I include data models since by their very nature, they are corrected and organized data sets (Potochnik et al., 2018).

[6] My use of analogies deviates to some extent from Harrison and Treagust (2000) and is more aligned with the evolved epistemology of Frigg and Hartmann (2020), Frigg and Hartmann (2006), and Harrison and Coll (2008). Specifically, Harrison and Treagust (2000) perceive all models as analogic while I reserve the typology for only a visual representation that linguistically compares a science target to an analog (Frigg & Hartmann, 2020; Frigg & Hartmann, 2006; Harrison & Coll, 2008).

[7] In the literature, other typologies have been documented such as idealized models, toy models, minimal models, phenomenological models, exploratory models, models of data (Frigg & Hartmann, 2020), and iconic models (Frigg & Hartmann, 2006). However, this thesis emphasizes examples where there is general consensus among the scientific model literature reviewed.

relevant[8] components that are essential for understanding their target system (Potochnik et al., 2018). Exemplary models visualize the interaction between abstract entities (Gilbert et al., 2000; Francoeur, 1997, as cited in Wang et al., 2014)—features that can have high relevance and low salience (Mason et al., 2013). They show the temporal and spatial changes in systems or phenomena (Mason et al., 2013; Potochnik et al., 2018). As processes in systems or phenomena, scientific models visually describe the mechanism[9]—what, how, and why (Schwarz et al., 2009; Windschitl et al., 2018). In addition, they are generated to construct, explore, manipulate/test, or make predictions about systems and phenomena (Hokayem & Schwarz, 2014; Potochnik et al., 2018; Wang et al., 2014; Wilkerson-Jerde et al., 2015). To convey the mechanisms inherent in systems and phenomena, scientific models that are drawings leverage semiotic tools—points, lines, blobs, and arrows—to convey meaning for concrete and abstract elements. Interestingly, semiotic tools can be polysemic (O'Donnell, 2020); thus, the meaning conveyed in scientific models is dependent on the context (Hokayem & Schwarz, 2014) in which the symbols are used. It is the context that disambiguates the meaning. For example, an arrow can have several meanings—importance, sequence, temporal relationship, causal relationship, motion, and force—based on the system or phenomenon under investigation (Tversky, 2011). By design, scientific models as forms of visual communication, incorporate cultural assumptions (Dunleavy, 2020; O'Donnell, 2020; Spencer, 2010; Tversky, 2011) and approximations, which impact their reliability, precision (Frigg & Hartmann, 2020; Willard, 2015), and interpretation (Dunleavy, 2020; O'Donnell, 2020; Spencer, 2010; Tversky, 2011).

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[8] Scientific models are dissimilar from their target system in ways that are irrelevant (Potochnik et al., 2018).

[9] Here, I deviate from Potochnik et al's. (2018) view of mechanism as a product rather than a process since in the project, I view drawings as products or physical/visual embodiments of mechanistic processes.

My interests in scientific models are threefold. First, as a science teacher, my compelling interest in scientific models emanates from the challenge to improve my instructional practice to prepare students for the NGSS that is slated to be implemented in 2023-2024[10] in New York State (NYS) in the adapted form known as New York State Science Learning Standards (NYSSLS) (New York State Education Department, 2019b, 2021). Specifically, in the standards, modeling appears as both a crosscutting concept and a science practice: systems and systems model, and developing and using models, respectively (National Research Council, 2012; New York State Education Department, 2019b). Prior to the NGSS, science teachers like myself "tended to directly provide models instead of encouraging students to construct models by themselves, which suggested [we] had [a] relatively narrow opinion about the nature and function of model[s]" (Wang et al., 2014, p. 213). A conceptually similar view is echoed by Hokayem and Schwarz (2014).

Second, what also compels me to further explore scientific models, is their versatility in making students' thinking visible (Lehrer & Schauble, 2010; Windschitl et al., 2018) and improving their knowledge of principles and their application in scientific systems and phenomena (Schwarz et al., 2009; Wang et al., 2014). As the crosscutting concept—systems and systems model—learners use scientific models/drawing activities as cognitive tools for systematically thinking (Harrison, 1992, as cited in Gilbert et al., 2000; Mayer, 1989; Passmore et al., 2017; Wu & Rau, 2019) about and comprehending scientific systems and phenomena. Specifically, scientific models reveal the degree to which students identify the relevant components in systems/system models/phenomena, build internal connections between the

[10] At the writing of this dissertation, NYSSLS implementation year is invariably changing due to the pandemic. This deadline is based on its most recent publication on the state's website.

relevant components, and integrate this information with prior understandings in a creative transfer of knowledge (Mayer, 1989; Schwarz et al., 2009). As a science practice—developing and using models—learners leverage drawing activities as constructive, communicative, and transformative tools (Schwarz et al., 2009; Wu & Rau, 2019). As a constructive tool, learners use drawing activities to represent science knowledge as a visual product (Gilbert et al., 2000; Passmore et al., 2017; Wu & Rau, 2019). As a communicative tool, learners use drawing activities to discuss science content with others (Kelly et al., 1987, as cited in Gilbert et al., 2000; Lyon, 2020; Passmore et al., 2017; Richmond, 2003; Schwarz et al., 2009; Treagust et al., 2002; Wu & Rau, 2019) such as their peers and instructors (Hokayem & Schwarz, 2014). Also, drawing activities allow learners to engage in internal dialogue via self-assessment (Liddament, 1993, as cited in Gilbert et al., 2000; Lyon, 2020; Wu & Rau, 2019). As a transformative tool, learners use drawing activities to solve problems, build knowledge/engage in sensemaking (Mason et al., 2013; Passmore et al., 2017; Schwarz et al., 2009; Wu & Rau, 2019), and predict the behavior of systems and phenomena (Hokayem & Schwarz, 2014; Schwarz et al., 2009; Treagust et al., 2002; Wilkerson-Jerde et al., 2015). The timeliness based on the NYS implementation schedule of NYSSLS (New York State Education Department, 2019b, 2021), the versatility of scientific modeling in visualizing students' thinking behaviors (Windschitl et al., 2018) so that teachers can monitor their progress (Wang et al., 2014), and its significance in successfully implementing the state (New York State Education Department, 2019b, 2021) and national standards (National Research Council, 2012) make the topic worthy of qualitative research (Tracy, 2010).

Third, I am also drawn to the topic for other reasons that make it worthy of research. As a doctoral student, I have had the privilege to come across empirical studies (Covitt et al., 2018;

Vasconcelos & Kim, 2020) that surprisingly proposed that the challenge in interpreting students' scientific models is more pervasive than I initially realized. For instance, researchers (Covitt et al., 2018) that methodically implemented professional development strategies to train teachers to interpret students' scientific models have unexpectedly found them to be fruitless because science teachers invariably resorted to interpreting models as right or wrong despite training. In another study making similar conceptual claims, Vasconcelos and Kim (2020)[11] report that "[a] common misconception among teachers is that models from textbooks are the only correct answer rather than an alternative form of representation" (Science teachers and scientific modeling section, para. 1). In the literature review of earlier work in the area of model-based instruction (MBI), Wang et al. (2014) acknowledge that both novice and experienced science teachers have difficulties in applying scientific models during instruction. From personal experience as a veteran science teacher and attendant at several workshops facilitated by reputable science teachers' networks in New York State and Maryland, I agree with Wang et al. (2014). According to the researchers, the nature of these difficulties is unknown. Treating the claim of Vasconcelos and Kim (2020) and other literature reviews as inductive data[12] (Glaser, 2002; Martin, 2019), I have used abductive reasoning[13] (Bryant & Charmaz, 2019; Charmaz,

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[11] Vasconcelos and Kim (2020) cite several questionable sources (Abell & Roth, 1995; Gilbert, 1991; Harrison & Treagust, 2000; Hokayem & Schwarz, 2014), but this claim was never directly investigated by the researchers and could not be substantiated by examination of three (Gilbert, 1991; Harrison & Treagust, 2000; Hokayem & Schwarz, 2014) of the available sources. Discussing the ethical issue surrounding this claim is beyond the scope of this dissertation, but the claim is an interesting one and is worthy of further qualitative investigation.

[12] A dictum of grounded theory (GT) is "all is data" (Glaser, 2001, as cited in Glaser, 2002).

[13] In the philosophical positioning section of Chapter 3: Methodology, I further address abductive reasoning as a creative reasoning/inferencing tool (Bryant & Charmaz, 2019; Shank, 1993, November; Tavory & Timmermans, 2014, 2019; Timmermans & Tavory, 2022) that is implemented in CGT for dealing with surprises, unanticipated puzzles, or unexpected/serendipitous/anomalous/counterintuitive observations (Timmermans & Tavory, 2022).

2016, 2020; Shank, 1993, November; Tavory & Timmermans, 2014, 2019; Timmermans & Tavory, 2022) to propose a tentative hypothesis.[14] That is, I believe that binary thinking[15] plays a role. Thus, my constructivist/constructionist worldview undoubtedly compelled me to ask, what are other explanations for this ingrained behavior? The durability of this binary interpretation—perceiving students' scientific model as wrong or right—aptly served as a motivating factor to pursue an alternative explanation, in essence, to reconstruct the traditional epistemology (Alcoff & Potter, 1993). I believed that prior researchers in their post/positivist approach, unfortunately, neglected to consider a relativist ontological perspective. A post/positivist approach undermines other ways of knowing and acts as an axis of oppression (Alcoff & Potter, 1993). Thus, my research goal is to investigate how secondary school science teachers interpret students' scientific models.

Situating the Study as a Constructivist Grounded Theory

In this section, I will discuss factors that contribute to the emergence of my plural outlook on knowledge in developing the project. For this, I will address (a) the iterative roles that my constructivist/constructionist worldview plays in the research design, (b) my approach to culture and its role in the project, (c) the rationale for adopting dual roles of

[14] To construct this initial hypothesis from secondary analysis (Glaser, 1962, as cited in Martin, 2019), (1) I collected literature across several disciplines, (2) made linguistic and epistemological connections, and (3) engage in constant comparison as discussed in Chapter 2 addressing systematic questions I routinely asked of the literature (Martin, 2019). But, I recognize that through reflexivity and memo writing about my data analytical decisions, other impressions will reveal themselves (Martin, 2019).

[15] I have selected the concept of "binary thinking" since it has an epistemological foundation (Martin, 2019) in several of the theoretical frameworks implemented in the study although it has been discussed in the interdisciplinary literature (Martin, 2019) as "dualism," "hierarchical thinking," "Cartesianism," "asymmetrical practices," "hegemony," and "secularism" (Boisselle, 2016; Carter, 2011; Higgins, 2016; Nisbett, 2003; Smith 2012; Walter & Walsh, 2018).

constructivist/constructionist in studying static drawings, (d) the philosophical tension between the constructivist/constructionist paradigmatic stance and positivism, (e) advantages of an emic perspective in translating the cultural meaning found in static drawings, (f) limitations of interpreting cultural meaning because of power dynamics, and (g) several examples from the literature that underscore how varying cultural contexts results in the plurality of knowledge production. In merging these ostensibly distant themes, I hope to illustrate to the readers of this dissertation, a raison d'être for using the constructivist/constructionist lens to reveal the relevant connections.

Constructivist/Constructionist Worldview

A researcher's worldview or paradigm guides the research project (Jones et al., 2014). According to Jones et al. (2014), it consists of the researcher's beliefs or assumptions. Thus, it serves multiple iterative roles in the research project. My philosophical orientation as a constructivist/constructionist[16] situates my research project. In this respect, it serves as a lens that shapes my beliefs about the construction of knowledge, frames the research questions, directs the

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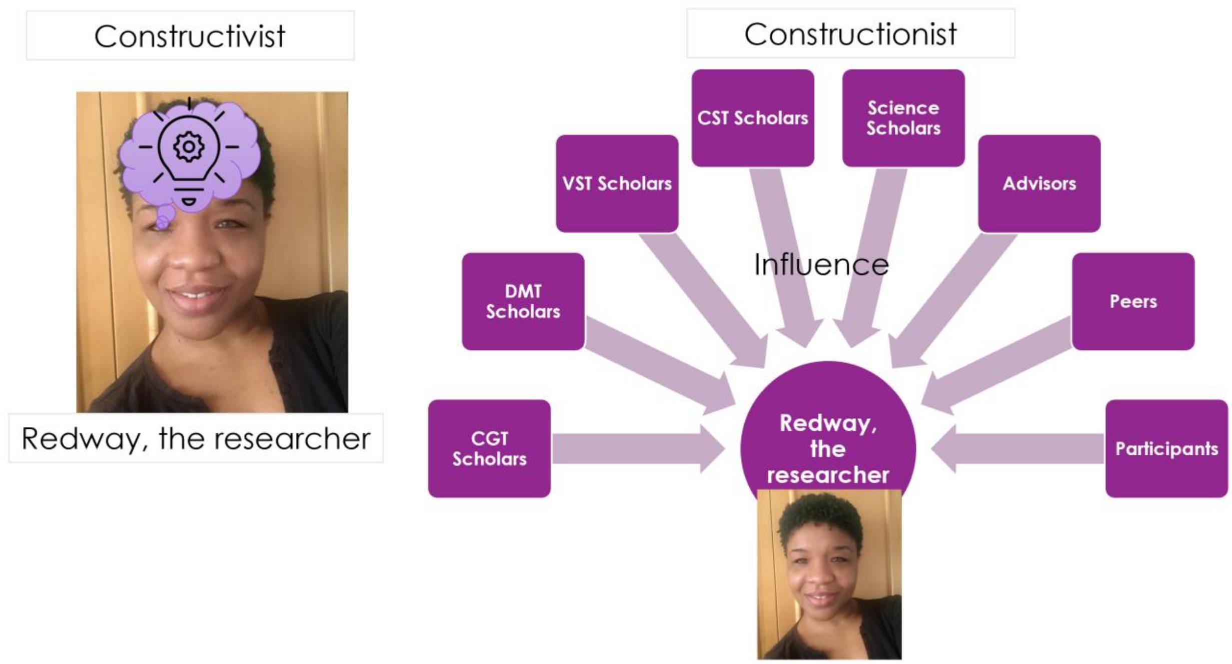
[16] In the research project, I choose to adopt the dual roles of constructivist/constructionist as represented by the compound expression because each role provides a partial understanding of scientific models (as addressed in the subsection: "Social Construction of Knowledge" of Chapter 1) and also my epistemological roles as a researcher/individual in interpreting the scientific models of participants/others. The constructionist lens emphasizes that as a researcher, I construct knowledge and make sense of reality through collective/social interactions (Ackermann, 2001; Gergen, 2015; Patton, 2014). That is, my project design is largely influenced by other CGT, DMT, VST, CST, and science scholars, advisors, peers, and participants. See Figure 1 and Figure 3. However, the constructivist lens emphasizes an individual interaction/agency, that is, knowledge construction originates in the head (Ackermann, 2001; Gergen, 2015; Patton, 2014). See Figure 1. I allude to this attribute in the subsection: "Power as a Consequence of Culture/Culture as a Consequence of Power." Therefore, as the research instrument, my research design and interpretation of the data is one of many possibilities because another CGT scholar can produce a different approach and explanation (Carcary, 2020).

theoretical frameworks adopted, and provides a rationale for the selected methodology, CGT. These are essential factors in the process of my qualitative research design.

Figure 1

Constructivist and Constructionist Conceptions of Knowledge



Note. The constructivist conception of knowledge denotes that knowledge construction originates in the head. The constructionist conception of knowledge denotes that knowledge is socially constructed.

My Approach to Culture

In the project, *culture*—the context of my study—is approached as shared knowledge (Wolcott, 2010, as cited in Jones et al., 2014; Lincoln & Guba, 2013; Rapley, 2018), shared meanings (Chandler, 2017; Dollie et al., 2020; Hall, 1997; O'Donnell, 2020), shared interpretations (Rohner, 1984, as cited in Salzman, 2018), shared traditions (Gergen, 2015), shared values (Ackermann, 2001; Chandler, 2017; Gergen, 2015; Gilbert et al., 2000; Kottak, 2010, 2015; Nanda & Warms, 2013, 2018; New York State Education Department, 2019a; Repko & Szostak, 2021; Willard, 2020), shared beliefs (Gergen, 2015; Gilbert et al., 2000; Kottak, 2010, 2015; Nanda & Warms, 2013, 2018; Saldaña & Omasta, 2018), shared attitudes (Saldaña & Omasta, 2018), shared rules (Ackermann, 2001; Chandler, 2017; Gergen, 2015; Hall, 1997; Nanda & Warms, 2013, 2018; Nisbett, 2003; O'Donnell, 2020; Smith, 2012; Willard, 2020), shared codes (Chandler, 2017; Delpit, 2006; Dunleavy, 2020; Gilbert et al., 2000), shared conventions (Chandler, 2017; Gergen, 2015; Hall, 1997; Hora et al., 2019), shared protocols (Aikenhead & Elliott, 2010), shared understandings (Aikenhead & Elliott, 2010; Dollie et al., 2020; McIntyre, 2021; Taber, 2014), shared norms (Chandler, 2017; Hall, 1997; Nanda & Warms, 2013, 2018), shared practices (Chandler, 2017; Dollie et al., 2020; Foucault, 2007; Foucault et al., 1997; Hall, 1997; Hora et al., 2019; Ladson-Billings, 1998; Nanda & Warms, 2018; Nisbett, 2003; Potochnik et al., 2018; Rapley, 2018; Saldaña, 2016; Saldaña & Omasta, 2018; Smith, 2012; Taylor, 2014), shared classification systems (Chandler, 2017; Nanda & Warms, 2018), shared symbol systems (Chandler, 2017; Nanda & Warms, 2013), shared sign systems (Chandler, 2017; Dunleavy, 2020; O'Donnell, 2020) that we use to make sense of the world and includes what I will call cultural truth—that is, shared truth by some (Gergen, 2015; Nanda & Warms, 2013; Salzman, 2018). Using this comprehensive conceptualization of culture, I will often use these terms[17]—knowledge, meanings, interpretations, traditions, values, beliefs, attitudes, rules, codes, conventions, protocols, understandings, norms, practices, classification/systems, symbol systems, sign systems, and truth—interchangeably to refer to

[17] These terms will serve as sensitizing concepts (Aldiabat & Le Navenec, 2018) or heuristic tools (Timmermans & Tavory, 2022) to guide my initial data collection and analysis.

what we know and socially agree upon as accepted attributes and collectively as a reminder of my perception of them.

Social Construction of Knowledge. As a constructivist/constructionist, I believe that knowledge is socially constructed (Sefa Dei, 2008, as cited in Dollie et al., 2020; Gergen, 2015; Jones et al., 2014; Kivunja & Kuyini, 2017; Lincoln & Guba, 2013) through the generation of products (Lincoln & Guba, 2013; Papert, 1993) and the "assemblage of signs and symbols (the semiotic organization)" (Lincoln & Guba, 2013, p. 52). My belief about the social construction of knowledge aptly applies to scientific models, specifically, the versions that are visually represented as static drawings and constructed using signs and symbols. It is for this reason that they are selected for my study. When deconstructed,[18] the semiotic organization of static drawings becomes visible (Spencer, 2010; Tversky, 2011). Because of this arrangement of the signs/symbols, I believe that a given meaning assigned by the interpreter and or creator is culturally assigned (Chandler, 2017; Dunleavy, 2020; Gergen, 2015; O'Donnell, 2020; Patton, 2014; Tversky, 2011). However, the culturally assigned meaning creates a shift in how the constructions are viewed. That is, they are regarded as "true for…all times and people" (Gergen, 2015, p. 28). This critical examination of static drawings is parallel with the notion of social construction of knowledge.

Using Constructivist/Constructionist to Challenge Positivism

Embracing a constructivist/constructionist philosophical stance also means that I recognize the limitation in the exactitude and certainty entrenched in scientism/positivism in the

[18] As Chandler (2017) notes, "[d]econstructing and contesting the realities [that drawings] represent can reveal whose realities are privileged and whose are suppressed" (p. 9).

production of knowledge. Thus, my decisions in the project are not constrained by what is traditionally perceived as true/right/rational/dominant ideologies (Bernal, 2002; Gergen, 2015; O'Donnell, 2020); therefore, they are not bound by disciplinary or official history/tradition/culture/epistemology (Alcoff & Potter, 1993; Connell, 2021, November 9; Gergen, 2015; Shank, 1993, November). More specifically, as a constructivist/constructionist, I adopt a subjective epistemology that acknowledges the existence of multiple kinds of knowledge/truths/meanings, while scientism/positivism recognizes an objective epistemology and the existence of a single knowledge/truth/meaning (Creswell & Poth, 2018; Jones et al., 2014; Kivunja & Kuyini, 2017; Lincoln & Guba, 2000; Repko & Szostak, 2021; Saldaña & Omasta, 2018). My subjective epistemology originates from my belief in multiple realities based on the existence of varying/multiple contexts (Aikenhead & Elliott, 2010; Jones et al., 2014; Kivunja & Kuyini, 2017). Thus, changing the context results in a change in reality (Delpit, 2006; Moore, 2007).

This ontological relativist position compels me to challenge/debate the positivistic interpretation of all empirical studies that address social constructs, which are cognitive products (Code, 1993) or constructions of the human mind (Glasersfeld, 1985, as cited in Gilbert, 1991; Groenland & Dana, 2020). As cognitive products, social constructs are devoided of objectivity/neutrality since they are produced by cognitive agents during shared/social practices which vary across social groups—in essence, culture (Code, 1993). Therefore, I argue that these empirical studies can produce multiple kinds of knowledge/truths/meanings/interpretations, which is antithetical to the ontological realist view of scientism/positivism (Kivunja & Kuyini, 2017; Lincoln & Guba, 2000), which privileges "itself as the (only) ontology" (Higgins, 2016, p. 188) and eliminates room for knowledge grounded in subjectivity (Fourie, 2021). In the case of scientific models, scientism/positivism assumes that truth can be carried by signs/symbols and that one semiotic organization is closer to the truth than others (Gergen, 2015) rather than an approximation of reality (Gilbert, 1991), thus producing an "objective drawing [which] privileges the rational and the logical" (Lyon, 2020, p. 298). However, as a constructivist/constructionist, I contend that it is social conventions that declare one form is closer to reality than another (Gergen, 2015). According to Potochnik et al. (2018),

> [i]t's something of a challenge to say exactly what's required for a model to represent a target, but some basic components are more or less agreed upon... The model must be like the target in the right ways... But[,] … models typically aren't exactly like the target systems they represent. They are often dissimilar from their targets in important ways… Something's needed to overcome that gap—the differences between the model and target—in a way that enables the model to nonetheless be about the target. It's increasingly believed that what fills that gap is social convention[19]—that is, scientists' shared practices in using and interpreting their models… Social conventions in modeling allow these intentions to be conveyed and shared. Social conventions enable modelers to see what similarities and differences they should expect between a model and a system, which in turn governs how the model should be interpreted and properly used. (p. 117)

In other words, scientific models are subjective drawings (Lyon, 2020) whose purpose is to dialogue with the self (Liddament, 1993, as cited in Gilbert et al., 2000; Lyon, 2020; Wu & Rau, 2019) or communicate with others (Kelly et al., 1987. as cited in Gilbert et al., 2000; Lyon,

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[19] Most likely based on social conventions of Western/Eurocentric perspective since science research has traditionally been based on the perspective of colonizers (Smith, 2012).

2020; Passmore et al., 2017; Richmond, 2003; Schwarz et al., 2009; Treagust et al., 2002; Wu & Rau, 2019).

In a field that has been traditionally rooted in the positivistic paradigm, it is worth considering other types of knowledge and ways of interpreting in order to change the conversation in science education research in light of these new understandings/revelations about the subjective nature of scientific models (Fourie, 2021). This can only be accomplished by "challenging the positivist norms [and lingering assumptions] we have all internali[z]ed as students and [science teachers] working in academia" (Fourie, 2021, pp. 20-21). We need to bring to the forefront, the types of knowledge that are subjective (Code, 1993; Fourie, 2021).

Cultural Meaning

In my research project, I habitually display a constructivist/constructionist paradigmatic stance that generally assumes that shared cultural experiences among members of a group result in the creation of shared constructions (Lincoln & Guba, 2013), for example, meanings (Hall, 1997) and artifacts (Kafai, 1994; Papert, 1993). As a member of the community of science educators, I believe that membership in the culture of science teachers will justifiably give me insider access to understand and interpret the communication styles (i.e., semiotics and meanings) that science teachers customarily leverage in interpreting students' scientific models (Hall, 1997; Hora et al., 2019). The ways in which I—the science teacher—make sense of the scientific models are an outcome of my relationships with others in the scientific community (Gergen, 2015). See Figure 1. In other words, my knowledge of how to explain, describe, and apply scientific models is socially constructed/learned from members of this community (Delpit, 2006; Gergen, 2015). Sharing this collective consciousness[20] (Chandler, 2017), I understand the "patterns of coordination" (Gergen, 2015, p. 10), that is, the rule/set of conventions (Delpit, 2006; Gergen, 2015) about what is un/acceptable in scientific model construction notably, the system of semiotic organization—words/objects/symbols/signs/space/context/environment (Delpit, 2006; Gergen, 2015; Tversky, 2011). Serving as a notable advantage, I believe that knowledge of the cultural codes or conceptual maps used among the various science domains equips me to translate/interpret (Hall, 1997) or analyze what is observed and heard during data collection. According to Boyatzis (1998), having this emic perspective from "training in the fundamentals and concepts of the fields relevant to the inquiry…provides some insight about…what to be ready to 'see'" (pp. 9-10). A similar sentiment is also echoed by Strauss and Corbin (as cited in Boyatzis, 1998).

Power as a Consequence of Culture/Culture as a Consequence of Power[21]

Despite having an emic perspective, I recognize its limitation; that is, differences in interpretation/meaning may surface when translating these cultural codes (Hall, 1997). This is a consequence of culture. It is these systems of differences[22] that create power dynamics (Foucault, 2006a, as cited in Schirato et al., 2020). As Hall (1997) notes,

> meaning is not straightforward or transparent and does not survive intact the passage through representation. It is a slippery customer, changing and shifting with context, usage and historical circumstances. It is always putting off or 'deferring' its rendezvous

[20] Until this dissertation, it had become natural for me to accept the invisibility of the ontological arbitrariness with this communication system (Chandler, 2017).
[21] The title for this subsection was inspired by the work of Hall (1997) which helped me initially to see a relationship between power and culture.
[22] Here, I point out how power reveals itself in one of four principles of power according to Foucault (Schirato et. al., 2020).

> with Absolute Truth. It is always being negotiated and inflected, to resonate with new situations. It is often contested, and sometimes bitterly fought over….We feel their contradictory pull, their ambivalence….They define what is 'normal,' who belongs—and therefore, who is excluded. They are deeply inscribed in relations of power...Meanings are often organized into sharply opposed binaries or opposites. (p. 10)

In my research, I am also cognizant of the structure of power (Jones et al., 2014; Smith, 2012) or power differentials/relations (Ellingson & Sotirin, 2020) between a researcher and participants that come with the risk of conducting an investigation. Therefore, what is re/presented will be influenced by my plural identities (Jones et al., 2014) such as being a Black female, master science teacher, researcher, systems thinker, and constructivist/constructionist.

Importantly, I believe that a similar power relation is at play when secondary school science teachers interpret students' scientific models (Delpit, 2006). In addressing the culture of power, Delpit (2006) acknowledges that "[i]ssues of power are enacted in classrooms" (p. 4). At the implicit level (Smith, 2012), these power relationships determine what is ab/normal (Foucault, 2007; Hall, 1997; Newman, 2016; Smith, 2012) and un/true (Gergen, 2015). Because of their subjective nature, they have serious implications for science instruction and assessment. In the conventional science classroom, these power dynamics in/visibly[23] expressed as marginalization and alienation become very pronounced when socially constructed non-Western/Indigenous knowledge/values/traditions are in conflict with the socially constructed

[23] Often the victims of marginalization/alienation recognize this maltreatment/mode of punishment (Foucault, 2007) while other onlookers simply see it as the status quo (Esposito & Evans-Winter, 2021), a system of norms (Nanda & Warms, 2018), and not the system of social control (Schwan & Shapiro, 2013) that it is. Thus, these onlookers fail to provide support to victims.

Eurocentric knowledge/values/traditions (Aikenhead & Elliott, 2010). In the literature, several scholars (Foucault, 2007; Nanda & Warms, 2013, 2018; Smith, 2012) draw our attention to a relevant point regarding socially constructed knowledge/rules/interpretations/meaning—*culture*. That is, what is considered normal is evolving and renegotiated (New York State Education Department, 2019a). A crucial point to remember is that meaning is plastic and is constantly being reviewed and edited over time (Lincoln & Guba, 2013; O'Donnell, 2020; Spencer, 2010). Therefore, the "interpretation of [normality is] not universal but must be located and situated in space and time"(Clarke, 2019, p. 7). The evolution/flux/modification reflects changes in internal and external power-knowledge[24] (Foucault, 2007) dynamics; therefore, normality can be contested. According to Foucault et al. (1997),

> all these rules or, … all these practices that were indeed governed by rules but also constantly modified through the course of history, seem to me to be one of the forms by which our society defined types of subjectivity, forms of knowledge, and, consequently, relations between man and truth. (p. 4)

In the backdrop of this statement, Foucault et al. (1997) underscore for science teachers that at the core, knowledge, truth, and rules are subjective. They are not the objective forms of reality that post/positivists portray them to be. As science teachers, we should be cognizant of these dominant knowledge systems (Alcoff & Potter, 1993; Connell, 2021, November 9), ideologies (New York State Education Department, 2019a; O'Donnell, 2020), and colonizing practices

[24] Unlike other compound expressions used in the dissertation, I adopt the hyphenated version for two reasons: (1) to preserve the form used in the literature cited and (2) distinguish the usage of the composite term from others that I have used interchangeably since Foucault (2007) sees power as a producer of knowledge and not it's equivalent. A detailed description of the power-knowledge nexus is beyond the scope of this dissertation but is available in Taylor (2014).

(Dollie et al., 2020) when interpreting students' scientific models in our diverse classrooms because they have the propensity to discredit other epistemological perspectives (Alcoff & Potter, 1993) and other "ways of thinking, values, and forms of expression" (New York State Education Department, 2019a, p. 11). What my study aims to provide are the thought processes that comprise these dominant knowledge systems and de/colonizing practice in reference to scientific models.

A conceptually similar/relevant notion regarding the power-knowledge dynamics involved in universal truth is raised by Gergen (2015). According to Gergen (2015), universal truth must be approached with caution because "when 'the truth' leaps from its location within a specific tradition/[culture,] we confront the possibilities for suppression, conflict[,] and oppression" (p. 11).

Cultural Context

From an ontological relativist position, I believe that individuals come to know and understand—that is, make sense of their world—based on the cultural context (Aikenhead, 2010; Aikenhead & Elliott, 2010; Alcoff & Potter, 1993; Hall, 1997; Higgins, 2016; Jones et al., 2014; Kivunja & Kuyini, 2017; Nisbett, 2003) of their experience. Thus, "knowledge is contextual" (Carmichael & Cunningham, 2017, p. 60). In the context of the United States, this relativist position assumes that a change in the cultural context—from a Western/Eurocentric/U.S.-centric/Cartesian[25] cultural perspective to a non-Western/Indigenous/other-than-Cartesian cultural perspective—results in a change in reality (Carter, 2011; Higgins, 2016; Nisbett, 2003;

[25] In the project, I have adopted the label/nomenclature of Cartesian for two reasons. *Cartesian* captures the attributes of binary/hierarchical thinking (Higgins, 2016) and *other-than-Cartesian* lacks the historical stigma of descendants of savages (Smith, 2012) or conquered people (Boisselle, 2016) as is the case for the label/nomenclature Indigenous.

Smith, 2012; Walter & Walsh, 2018), thus, suggesting diverse dimensions and spectra for interpretation (Martin, 2019). The notion that the only reality or knowledge is that of Western/Eurocentric/U.S.-centric/Cartesian culture presents a distorted view and limits/threatens our understanding of our world (Barad, 2000; Boisselle, 2016). These ontological assumptions of Western/Eurocentric/ U.S.-centric/Cartesian culture fail to recognize that multiple realities are possible in which Western/Eurocentric/U.S.-centric/Cartesian thought is one of many (Bernal, 2002; Walter & Walsh, 2018). Thus, multiple realities result in a subjective epistemology where multiple meanings/kinds of knowledge—epistemological pluralism (Carter, 2011)—can be constructed when interpreting a scientific model. When teachers treat scientific models with a binary view of the world, the plurality of knowledge is denied/dismissed.

In this dissertation, my interpretation of Western/Eurocentric/U.S.-centric/Cartesian and non-Western/Indigenous/other-than Cartesian cultures is largely guided by seminal scholarships—Carter (2011), Higgins (2016), Nisbett (2003), and Smith (2012). Thus, I view differences between the cultures in terms of membership in a language/tribal/racially minoritized/ethnic group, ways of thinking about the world, and a nation's colonial affiliations/global ranking/geographic location/wealth. For example, I perceive non-Western/Indigenous/other-than-Cartesian cultures as individuals/people whose dominant language is not English, who belong to a racially minoritized/ ethnic group, who are descendants of a developing/colonized country, who self-identify as native/first people, and or who make sense of the world using plural/multiple/diverse thinking. However, I perceive Western/Eurocentric/U.S.-centric/Cartesian culture as individuals/people who are descendants of settlers from an English dominant/colonizing/rich/First World nation, and or who make sense of the world using binary/hierarchical thinking. As discussed in Chapter 4, these cultural factors aided in categorizing themes that emerged from the participants. See Figure 13: CGT Model of How Science Disciplinary Culture Works/Operates.

A Few Examples of Epistemological Pluralism. Though they are not from the subdiscipline of science education, nor do they integrate static drawings, several scholars (Gergen, 2015; Hall, 1997; Harding, 1986; Nisbett, 2003; Trinh, 1989) provide powerful examples that demonstrate the epistemological pluralism in the social construction of knowledge. I believe a similar relationship—that is, a type of epistemological pluralism—is evident in the interpretation of scientific models. Thus, my research provides an illustrative example from science education.

To illustrate epistemological pluralism, I must examine the situational ethics of a phenomenon—that is, how do other cultures interpret the same phenomenon? Situational ethics assume the existence of multiple contexts or what I will on occasions call multiple perspectives. Thus, "each circumstance is different and that [as a] researcher…[I] must repeatedly reflect on, critique, and question [my] ethical decisions" in conducting and writing the literature review, and in collecting and analyzing the data (Tracy, 2010, p. 847). As a constructivist/constructionist with a balanced axiology, the selected scholars provide the opportunity to convey my integration of situational ethics in the literature review in the form of epistemological pluralism of various phenomena.

Example 1: The Fish in the Pond. In an empirical study with American students at the University of Michigan and Japanese students from Kyoto University observing "eight color animated underwater vignettes" (p. 89) of fish in a pond, Nisbett (2003) provides a salient example of the construction of multiple meanings/interpretations/kinds of knowledge/truths from observing the world through the lens/perspectives/ social realities of Western and non-Western cultures. The study revealed that Japanese students were more likely to recall the presence of contextual components—rocks, water, bubbles, decorative plants, and animals—while American students were more likely to recall the presence of the focal component—the fish.

Example 2: Social Structure and Social Interaction. In a philosophical/historical examination of the anthropological models of social structure, Harding (1986) points out that multiple meanings/interpretations/kinds of knowledge/truths are possible from experiencing the world from the lens/perspectives/ social realities of White men and White women. “Social actors who are women appear to make significantly different and broader assumptions about what constitutes social interaction and social structure than do either the men in their own culture or (masculine) social scientists” (Harding, 1986, p. 88). In essence, social structure and interaction shape our understanding and knowledge of the world (Harding, 1993).

Example 3: Elements of the Material World. In a cultural communication study of language as a representational system that constructs meaning, Hall (1997) reveals that often in cultures, multiple meanings/interpretations/ kinds of knowledge/truths are assigned to a given element found in the material world. However, the meaning or value emerges from the context of use. For instance, a stone can be interpreted as “a stone, boundary maker or a piece of sculpture” (Hall, 1997, p. 3). It is membership in a cultural community that determines similar interpretations.

Example 4: Anthropological Writing. In a literary and cultural criticism of social anthropology, Trinh (1989) offers new insights (Nye, 1998) or other angles (Davies, 1991)—from the experiences of women of color feminists—for the interpretation of anthropological writing. From the perspectives of natives, Trinh (1989) perceives anthropological writing as “fiction[al] from the standpoint of language” (p. 70) and not the objective science that is pervasively portrayed by post/positivists. Language is based on systems of signs embedded with values and prejudices (Hall, 1997; Trinh, 1989). Trinh (1989) clarifies that "descriptions of native life [found in anthropological writing] although not necessarily false or unfactual, are "actor-oriented," that is to say, reconstructed or fashioned according to an individual's imagination. Thus, with roots embedded in semiology—the study of signs/symbols—anthropological writings "should itself be treated in semiological terms" (p. 71).

Example 5: Traditional Interpretations of Death. In highlighting how traditions shape our interpretation of death, Gergen (2015) offers multiple interpretations rooted in traditions that I believe readers of this dissertation will recognize. According to Gergen (2015), death can be conceptualized as (a) "termination of bodily functions," (p. 5) (b) "gone to heaven," (p. 5) (c) "beginning a new cycle of life in reincarnation," (p. 5) (d) change in atomic composition, and (e) easing one's burden. Each traditional interpretation whether derived from scientism/positivism or spirituality is a socially accepted pluralistic way in which we make sense of death.

Research Validity

In addressing the validity concerns of the project, as a new researcher with a constructivist/constructionist paradigmatic stance, I adhere to the social conventions of other qualitative researchers and CGT scholars since their work serves as the epistemic criteria. I also recognize that I must engage in research border crossing (Aikenhead & Elliott, 2010; Carter, 2011; New York State Education Department, 2019a; Rasheed, 2001, 2006; Snively & Corsiglia, 2001) and use this colonial term/signifier—validity—that is ubiquitous in quantitative research (Esposito & Evans-Winters, 2021) to achieve academic acceptance/success. In doing so, I succumb to the institutional power "regime of truth…that is, the types of discourse [and rhetoric] it accepts and makes function as true" (Foucault et al., 1997, p. 131).

Serving as the research instrument (Aldiabat & Le Navenec, 2018; Creswell & Poth, 2018; Jones et al., 2014; Mason, 2018; Merriam, 2007; Ravitch & Carl, 2019; Saldaña & Omasta, 2018) in data collection and analysis, I recognize that my beliefs, values, and assumptions can influence my theoretical and paradigmatic orientations. Thus, in making my worldview and theoretical perspectives explicit, I engage in reflective and reflexive processes (Carmichael & Cunningham, 2017; Charmaz, 2016, 2020; Jones et al., 2014; Ravitch & Carl, 2019; Saldaña & Omasta, 2018)

> to critically examine the layers of [my] beliefs,…values, and assumptions…[about] what [I] choose to focus on, how [I] frame it…, how [I] collect data and engage with participants, and how [I] interpret and analyze the data…and [will] write about the findings. (Ravitch & Carl, 2019, pp. 39-40)

In the project, I accomplish these reflective and reflexive processes using memos, member reflection, audit trails of data analysis, and professional dialogues with advisors and peers to address these validity concerns (Carcary, 2020; Creswell & Miller, 2000; Frey, 2022; Given, 2008; Tracy, 2010). Specifically, in the study, both internal and external auditing mechanisms (Frey, 2022; Given, 2008) were implemented. With respect to the internal auditing protocol, members of the dissertation committee examined the ongoing analytical decisions I have made. For external auditing, I sought the advice of a veteran researcher and an objective colleague who is an experienced science educator (Rhee, personal communication, July 18, 2022). Using the data management capabilities of NVivo (QSR International Pty Ltd, 2020)—a type of Computer Aided Qualitative Data Analysis Software (CAQDAS) (Bowen, 2009; Carcary, 2020)—to facilitate the process, both sets of auditors reviewed the (a) versions of the codebook as it evolved into its final form, (b) data analysis/synthesis products (i.e., initial theorizing and emerging diagrammatic displays), and (c) analytical memos to "provid[e] oversight and reflexive commentary as initial decisions [were] made" (Given, 2008, p. 42).[26] Other procedural safeguards that were undertaken include crystallization/triangulation of theoretical frameworks, methods, and data sources, interrater reliability with peer reviewers, and dissertation advisor (Rowlands et al., 2016; Tracy, 2010).

Research Delimitations

In this study, two relevant boundaries have been established. First, the research focuses primarily on scientific models that are made from drawings—static—instead of other types of scientific models such as "diagrams, flow charts, equations, graphs, physical replica[/scale models,]" (Windschitl et al., 2018, p. 115) and analogies (Frigg & Hartmann, 2006; Frigg & Hartmann, 2020; Harrison & Coll, 2008; Harrison & Treagust, 2000). I have selected drawings as the scientific model of interest because (a) they are widely used in the science education literature (Chang et al., 2014; Leutner et al., 2009; Mason et al., 2013; Passmore et al., 2017; Van Meter, 2001; Wilkerson-Jerde et al., 2015; Wu & Rau, 2019) and classrooms, (b) these are types of models that are invariably addressed at science workshops and conferences that I attend, (c) I believe that the cognitive demand for students to initiate model construction is lower for drawing activities than flow charts, analogies, equations, and graphs which are rooted in language and mathematical systems, respectively, (d) I assume the financial demand for students and teachers to construct drawings are lower than physical replicas, and (e) like other researchers (Schwarz et al., 2009), I perceive drawings and diagrams as the same. Therefore, discussing scientific models other than drawings is beyond the scope of this work.

[26] See also Bowen (2009) and Carcary (2020) for additional audit trails guidelines.

Second, the research focuses on recruiting participants that are secondary school science teachers, who use MBI and teach physical science.[27] As a secondary school science teacher who uses MBI, I assume having an emic perspective would be advantageous in data collection and analysis. Moreover, historical analysis of science education scholarship (Chang et al., 2014; Hodgkiss et al., 2018; Mason et al., 2013; Passmore et al., 2017; Wilkerson-Jerde et al., 2015) demonstrates that physical science is a suitable domain for research since it applies signs and symbols in capturing low salience and high relevance features of scientific phenomena and scientific systems.

Research Contribution and Significance

I believe the aim of empirical research is to construct and contribute knowledge that "enhance[s]…community processes" (Smith, 2012, p. 130) for both scholars and stakeholders. Thus, my study will provide an insightful theoretical contribution to science education in the form of a CGT. The CGT will (a) extend the knowledge about how teachers interpret students' scientific models to influence district, state, and national policies; (b) improve model-based assessment (MBA) practices for teachers; (c) hopefully, feed back into the literature to generate ongoing research (Tracy, 2010); and, (d) integrate the literature by connecting theories and their associated subdisciplines that are epistemologically distant/close (Repko & Szostak, 2021; Tracy, 2010). I hope the study will reveal a "mix of the scientific practices of the colonizer and the colonized" (Boisselle, 2016, p. 1) when the science teachers thought processes are revealed. In addition, this study will bring to light that the scientific practice of interpreting students'

[27] As discussed in Chapter 3: Methodology (see paragraph 5 in subsection titled Participants), in the field, I will expand the sample frame to include all science domains if recruitment becomes challenging with a narrow sampling frame.

scientific models is not immune to science teachers' subjectivity including their cultural influences (Stanley & Brickhouse, 1994, as cited in Boisselle, 2016). Since science teachers serve as arbiters of "what counts as valid knowledge in [science classrooms]" (Bernal, 2002, p. 106), the success of MBA in the NGSS and NYSSLS is largely dependent on their understanding/interpretation of this scientific process (Wang et al., 2014). As a process that relies upon interpretation, an analytical framework ought to consist of "a range of equally acceptable approaches to interpreting [scientific models]" (Rose, 2013, as cited in Lyon, 2020, p. 300) and "multiple models of the same target" (Potochnik et al., 2018, p. 118) thus, respecting the plurality of knowledge construction. In the arena of NGSS and NYSSLS, I advocate for top-down change─that is, pushing gatekeepers to accept a variety of scientific models (Delpit, 2006).

Organization of the Dissertation

In this CGT study, the chain of logic is the organizational approach that is implemented in the writing process. Chapter 1 introduces scientific models as effective tools for visualizing students' thinking, the pedagogical need to understand the thought processes leveraged by teachers who attempt to integrate this tool as a part of their instructional and assessment practices, and culture as the context for examining these invisible thought processes. It also includes the role my constructivist/constructionist paradigmatic stance will play in understanding and explaining secondary science teachers' thought processes when interpreting students' scientific models.

Chapter 2 addresses the literature review which includes the a priori theoretical frameworks that integrate a range of perspectives to guide the study and commences with a revelation of my thought processes and research choices that have led to the selection of the theoretical frameworks—decolonizing methodologies theory (DMT), visual semiotic theory

(VST), and cultural studies theory (CST). The logic of how each conceptual framework feeds into the next identifies the gap in the literature and will be bridged by my study.

Chapter 3 justifies why a CGT methodology is aptly suited for answering the two investigation questions and how the data collection instruments, and data analysis methods complement the methodology. In addition, measures of trustworthiness, ethical concerns, and limitations of the study are also addressed.

Chapter 4 reveals the research findings and is framed by methodological decisions that guided the codebook development and management protocol, along with unexpected twists and turns along the journey. In addition, the two research questions are answered.

Chapter 5 shares how others can benefit from the study including academics, science teachers, district leaders, state assessors, future researchers, and dissertation candidates. In addition, two relevant limitations of the study are addressed. It concludes with a personal reflective narrative of my journey through the dissertation process.

CHAPTER 2: LITERATURE REVIEW

As introduced in Chapter 1, this study seeks to create a CGT that explains the thought processes used by secondary school science teachers to interpret students' scientific models that are comprised of drawing activities. From a comprehensive review of the theoretical and empirical literature related to the plural interpretations of signs and symbols—semiotics—I have organized the current chapter into a few sections to convey the thematic organization and interpretation that has shaped and facilitated my understanding of the invisible thought processes that science teachers use when interpreting students' scientific models that are comprised of drawing activities.

Largely influenced by my skill as a systems thinker—my ability to see the interaction of multiple parts of a complex issue—I have ambitiously foraged the empirical and theoretical literature using various keywords: "scientific models," "drawing activities," "visual representations," "semiotics," "decolonizing science," "cultural/communication,"[28] "epistemology," "ontology," "axiology," "theory," "constructivist/grounded theory," "post/positivism," and "constructionism/constructivism." This process has taken me to multiple sub/disciplines that ostensibly appear to be epistemologically distant. Equally importantly, these keywords are a product of the systematic questions that I have routinely asked of the literature during the search such as: How do scholars study scientific models in a way that is relevant to my classroom instruction? Since researchers tend to study scientific models as drawing activities, what are drawings composed of? If drawings are composed of signs and symbols, how are they interpreted? If signs and symbols have multiple interpretations, why do empirical scholars in their study of drawing activities struggle to understand the intangible thought processes

[28] For the composite terms, the keyword search string leveraged the Boolean operators AND/OR.

employed by teachers when interpreting these models generated by students? What unfolds in the subsequent sections in this chapter as illustrated by the theoretical framework graphic (see Figure 3) is an interdisciplinary explanation for the evasive factors that contribute to thought processes used by science teachers in interpreting students' scientific models. Guided by the parameters set by the keywords, the relevant stages in the mechanism of how I derived this interdisciplinary explanation are underscored by the headings and subheadings that organize the chapter.

The chapter commences with a summary of relevant studies for instructional[29] best practices for the two types of drawings—static and dynamic—based on typical science classroom resources. In section two—the nature of drawings—I describe the cognitive benefits, the criteria for achieving them, and provide a rationale for the subjectivity of meaning conveyed by drawing activities. In the third section, I describe how symbol systems are represented to convey meaning.[30] The fourth section—the methodological grounding—provides a rationale for borrowing the concepts, terms, theories, assumptions, and definitions from the selected sub/disciplines to guide my initial understanding of the central phenomenon. The corresponding subsection shows the significance of my study by highlighting the relevant areas where the selected theories are connected, pinpointing the pivotal role they play in re/shaping my understanding of the research landscape, and exposing the gap in the literature that will be

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[29] While the major portion of the dissertation focuses on the assessment practice of interpreting students' scientific models, the purpose of this section is to also show the contributing studies that has shaped my own thought process and research decisions.

[30] Based on DMT, VST, and CST, I assume that these symbol systems and their meanings are not universal and are based on the perspective of the Western/Eurocentric perspective since science research has traditionally been based on the perspective of colonizers (Smith, 2012).

bridged by my study. The chapter concludes with a summary of major themes from the literature review and emphasizes the need for my study to contribute to the body of research knowledge.

Instructional Best Practice for Drawing Activities[31]

In Spring 2020, as a first-year doctoral student in the nascent stage of my literature review on scientific models, searching the bibliographic databases and online search engines for scholarly articles using the keyword “scientific models” proved to be unproductive. What I expected to find were empirical and theoretical studies that addressed scientific models in the manner I had implemented them in my classroom—as “drawings.”[32] However, what several days of effort generated were mostly irrelevant articles which initially led me to conclude that either scholars were not studying scientific models in the traditions of the NGSS and NYSSL or I was using a keyword that was too general. Deciding on the latter, I diligently continued my search which proved fruitful with the discovery of extant literature, Wu and Rau (2019). Explicitly drawing on the work of Wu and Rau (2019) revealed that scholars are studying scientific models as “drawing activities”—that is, as marks on a receptive surface (Lyon, 2020). Inspired by articles referenced by Wu and Rau (2019), this section outlines prior work on drawing activities as they relate to best practices for my classroom instruction. When paired with science resources—expository texts, illustrations, animations, and exploratory activities—that students can use to derive discipline content, scientific models can be constructive, communicative, and

[31] I have selected this title because I want this section of the dissertation to be a must-read for science teachers who are new to implementing scientific models in their classroom but may not choose to read the entire thesis.
[32] At this stage in the research, I had not made the association between drawing activities and scientific models.

transformative tools. This was exactly what I needed to transform my classroom practice for integrating scientific models in a way that aligned with the traditions of the NGSS and NYSSLS.

Static Drawing Activities Paired with Expository Text and an Illustration

Drawing activities can serve as constructive tools (Wu & Rau, 2019). Specifically, learners leverage static drawings to translate content understanding from science resources into a visible product (Van Meter, 2001). In an illustrative example of the constructive nature of drawing activities, Van Meter (2001) investigated the best instructional approach to allow learners to generate a static image of their learning from an expository science text.[33] In the control group,[34] American fifth and sixth-grade students read an expository science text describing the features of the nervous system and viewed two complementing illustrations. In the first of the three variations of the experimental group, the learners read the expository science text and constructed their drawings. In addition to performing the tasks of the first variation, learners in the second variation viewed the illustrations and compared their drawings with the reference illustrations. Learners in the third variation performed identical tasks to the second condition, but they also received instructional support in the form of verbal scaffolding questions. The results showed that learners who received the scaffolding questions constructed the most accurate drawings and scored significantly higher on the free-response posttest.

Van Meter (2001) suggested that for students to construct accurate and comprehensive drawings of their understanding of expository science texts, instructional scaffolds are needed to enhance their achievement. These findings support my experience with drawing activities in the

[33] I believe this is a good entrance point for novice science teachers of drawing activities.
[34] In summarizing these studies, I often use quantitative terms such as control group and experimental group which readers of this dissertation—science teachers—will appreciate to facilitate their understanding.

middle school science classroom. Also, it clarifies an issue that I have experienced with drawing activities. Specifically, I have noticed that most students struggle to generate accurate and comprehensive drawings despite having written scaffolds in the form of checklists. However, when scaffolds are verbally addressed, the accuracy and comprehensive feature of the drawings improve. This implies that the mode of delivery of the scaffolds is relevant to the quality of the drawing product created by students. Some modes present a higher cognitive demand than others.

Static Drawing Activities Paired With Expository Text Lacking an Illustration

The presence or absence of complementary illustrations impacts the role of drawing activities as constructive and transformative tools for comprehending science content. Leutner et al.'s (2009) study addressing the effect of external pictorial transformation (i.e., drawing activities) and mental pictorial transformation on learners' comprehension of expository science text without illustrations supports the high cognitive demands posed by drawing activities. In the control group, German 10th graders read an expository science text addressing the dipole nature of water molecules. In the first of three variations of the experimental group, learners read the expository text and constructed mental pictorial representations of the text. In addition to reading the text, learners in the second variation constructed external pictorial representations (i.e., drawings) of the text. In the third variation, learners constructed drawings followed by mental representations of the text. The results from a comprehension test revealed that learners who constructed drawings showed poor comprehension due to high cognitive demand. Therefore, less mental transformation occurred. However, learners who constructed mental pictorial representations showed increased comprehension due to lower cognitive demand.

Leutner et al. (2009) recognized that drawing activities are not universal instructional strategies for every expository science text. This is very relevant to current classroom practice where science educators might have the misconception that if the drawing activity worked for one expository text, it should work for all. This subtle nuance makes a difference in the use of drawing activities. Moreover, science educators might misconstrue students' poor assessment performance after using a drawing activity with expository science text without illustration as an indicator of poor reading ability instead of the high cognitive demand placed by drawing activities.

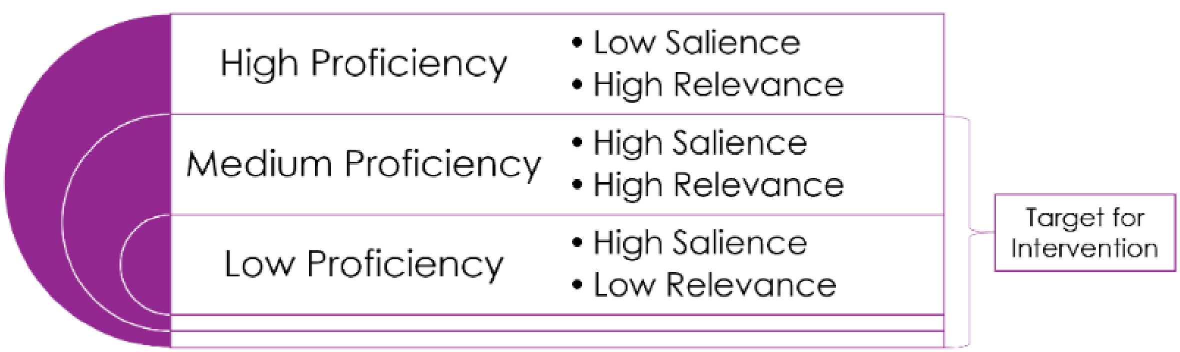
Static Drawing Activities Paired with Animations

When paired with animations lacking verbal accompaniment, drawing activities are powerful constructive, transformative, and communicative tools (Wu & Rau, 2019). Mason et al. (2013) in their study addressed this noteworthy feature of drawing activities to foster comprehension of complex phenomena. In the control group, Italian seventh-graders viewed an animation of Newton's Cradle and explained the mechanism of the phenomenon. In the first of two experimental groups, learners viewed the animation, traced six randomly sequenced dotted cards addressing stages of the phenomenon, and explained the mechanism. In the second of two experimental groups, learners viewed the animation, constructed six drawings that represented stages of the phenomenon, and explained the mechanism. The results from immediate and delayed posttests showed that learners who constructed self-generated drawings had a proficient understanding of the phenomenon compared to learners in the other groups. Learners with proficient understanding captured features of the animation that were highly relevant and inconspicuous.

Mason et al. (2013) skillfully demonstrated that drawing activities are more than the motoric function of putting pencil to paper and aesthetic appeal as documented in the traced activity. Drawing activities engage students in the mental processes of extracting perceptually salient and relevant content, organizing, and transforming the content to reveal new and deeper understanding. I believe this is important, especially in assessing the quality of students' work to determine novice learners from proficient learners. Novice learners will not capture the relevant content that has low salience, which would be observed in drawings of more proficient learners. This is important in helping teachers recognize the features of comprehensive drawings and not be confused by the illusion of aesthetics. See Figure 2.

Figure 2

Theoretical Model of Interpreting Drawing Activities Proficiency



Note. Created from the empirical literature on drawing activities.

Dynamic Drawing Activities

Combining dynamic drawing activities with learners' explanations makes drawing activities comprehensive, cognitive, constructive, transformative, and communicative tools. Chang et al. (2014) investigated the benefits of student-generated dynamic drawing activities (i.e., animations) in integrating the macroscopic world with the inconspicuous view of the submicroscopic world in the middle school chemistry classroom. American seventh-graders observed the chemical reaction between hydrochloric acid and calcium carbonate. Learners generated dynamic drawings in Chemation (i.e., a computer visualization tool that allowed students to create dynamic drawings) followed by verbally responding to six probing questions. The data showed that advanced learners more often constructed animations that revealed the intermediate processes of bond destruction and formation. When engaged in retrospective dialogue with the interviewers about their dynamic drawings, advanced learners were skilled at communicating an integrated understanding of the temporal and spatial changes in the phenomenon by relating their chemical background knowledge to corresponding features of the dynamic drawing. Less proficient learners were not able to make these inferential connections. Consequently, their drawings appeared static. Specifically, the drawings of novice learners included only the reactants and products and lacked the less perceptually salient but highly relevant intermediate stages that were involved in the mechanism.

Chang et al. (2014) pinpointed the benefits of using dynamic drawing activity in detecting gaps in students' conceptual understanding. Using dynamic drawings, science teachers can qualitatively identify students' zone of proximal development (Harrison & Treagust, 2000; Vygotsky, 1978) for subsequent scaffolding and enrichment exercises. This approach makes dynamic drawings more useful than their static counterparts in formatively assessing students' conceptual understanding.

Multiple Representations of Drawing Activities

The complex features of a phenomenon can be revealed via revising mental models using multiple external representations. The form of external representations influences the cognitive, constructive, communicative, and transformative tools that learners use to express their understanding of the phenomenon (Wu & Rau, 2019). Wilkerson-Jerde et al. (2015) analyzed the shift in American seventh-graders modeling practices and reasoning abilities as they interacted with various representational technologies while studying the diffusion of smells from oranges and clementines. Learners brainstormed, explored, represented, evaluated, and revised their ideas about the phenomenon using drawings, animations, and computational simulations. Interaction with each external representation allowed learners to convert their personal experiences into a coherent and sophisticated explanation of the mechanism of smell diffusion. Using a schematic template, the drawing activity allowed learners to identify and represent relevant components of the mechanism. The stop-motion animation exercise allowed learners to represent the temporal and spatial changes of their smell particles in a system. The StageCast simulation allowed learners to create and test rules about the behavior of the smell particles to generate quantifiable results.

Wilkerson-Jerde et al. (2015) offered several examples of using various types of representational media in the classroom. I believe that this study clearly showed that pencil and paper activities are not the only instructional tools that are available to science teachers for designing effective modeling activities. What this study implies is that students who are disengaged during the disciplinary practice of revising models (Passmore et al., 2017) after their initial pencil and paper drawing activity have other engaging options. Animations and simulations provide alternatives for teachers to proceed in the lesson with the scientific practice of revising models while still engaging learners (Shen et al., 2014). Also, simulations allow learners to integrate computational tools in science “to explore concepts that were previously inaccessible” (Resnick, 1996, p. 255). In addition, the flexible and purposeful use of concurrent models (Harrison & Treagust, 2000) illustrates to students that models have limitations. In other words, no model completely represents reality (Harrison & Treagust, 2000).

Semiotic Organization of Drawings and Their Meaning

Drawings use symbol systems to convey the meaning of content and context (Tversky, 2011). Decoding and interpreting these symbol systems requires knowledge of in/formal rules (Barnes, 2017; O'Donnell, 2020; Salen & Zimmerman, 2003) to make sense of constructions (Lincoln & Guba, 2013). Meaning is not self-evident (Christidou et al., 2023). Unlike photographs that are classified as indexical—signs/representations that are physically/directly connected/related to objects they portray (Spencer, 2010; Tversky, 2011)—drawings are classified as symbolical according to the Peircean classification system[35](Peirce Edition Project, 1998; Tversky, 2011). That is, they are signs/representations that are based on arbitrary conventions[36] that are shared in cultures (Barnes, 2017; Chandler, 2017; Dunleavy, 2020; Spencer, 2010). Therefore, meaning can only be derived from the context and knowledge of the cultural norms (Salen & Zimmerman, 2003).

The Nature of Drawings

A review of the literature shows that drawings are forms of visual communication (Lyon, 2020; Tversky, 2011). Consisting of actual or virtual marks (Tversky, 2011) on a receptive surface (Lyon, 2020), drawings convey meanings (Barnes, 2017; Tversky, 2011) for

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[35] Discussing the historical legacy of the Peircean classification is beyond the scope of this dissertation but a more detailed description can be found in Peirce Edition Project (1998).
[36] According to the Saussurean arbitrariness principle of signs, despite the ontological arbitrary relationship between a signifier and signified (See Figure 5), "[i]ndividuals have no power to change a sign in any way once it has become established in the…community" (Chandler, 2017, pp. 27-28). However, Delpit (2006) advocates for students "to learn about the arbitrariness of …codes and about the power relations they represent" (p. 45).

literal/concrete/visible and metaphoric/abstract/invisible elements showing their temporal and spatial relationships (Tversky, 2011). For science teachers, the most inspirational work in understanding the nature of drawings is the seminal work of Tversky (2011).

For learners, Tversky (2011) proposes that drawing activities have tremendous cognitive benefits. A few of these benefits include (a) facilitating the development and organization of thought, (b) alleviating limited short-term memory (c) increasing long-term memory, and (d) encouraging the generation of new insights/relationships/inferences/interpretations/meanings. To achieve these benefits, much is required of learners such as competency in spatial thinking/mental transformation, schematization, knowledge of disciplinary core ideas, and how to combine them with drawings.

Drawing activities have limitations[37] in conveying objective meaning. The primary limitation stems from the schematization process. *Schematizatio*n, a reductive process, requires several subjective decisions[38] to be made when studying systems and phenomena such as (1) What elements to include/exclude? (2) What elements to reduce/expand? (3) What elements to sharpen/level? (4) What elements to distort/exaggerate? (5) How should marks and space be arranged on a page to show proximity/temporality/preference? (6) How do you represent aspects

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[37] From these limitations, I abductively reason (Bryant & Charmaz, 2019; Shank, 1993, November; Tavory & Timmermans, 2014, 2019; Timmermans & Tavory, 2022) that drawings that are scientific models are subjective because there are plural possibilities from each creator.

[38] Besides the subjective decisions underscored, the degree to which these features should be implemented (Potochnik et al., 2018) as re/presentations of invisible assumptions—"made without regard for whether they are true, often with full knowledge they are false (see McMullin, 1985)" (Potochnik et al., 2018, p. 99)—further complicates the construction and interpretation process.

of reality?[39] According to Tversky (2011), the ability to make these types of subjective decisions comes with knowledge of the context of a system and experience with various contexts.

Noteworthy Examples of Rules Involving Symbol Systems

Tversky (2011) offers a few examples of rules involving symbol systems that I believe will be beneficial during the data collection and analysis processes of this project. These rules address spatial and temporal arrangements[40] to demonstrate abstract and concrete ideas, and the use of marks to convey importance.

Example 1: Spatial and Temporal Groupings. By convention, the placement of objects closer together usually indicates similarity, and further apart suggests dissimilarity. To illustrate (a) hierarchies, arrange and separate objects; (b) quantity, group by amount; (c) continuum or chronology, arrange objects horizontally; (d) order or interval, arrange linearly; and (e) preference, arrange vertically (Tversky, 2011).

Example 2: Marks to Convey Importance. *Glyphs*—simple marks—such as points/dots, lines, blobs, and arrows are ideal for visualizing the invisible and making generalizations. Their meanings are context-dependent. By changing the (a) size, (b) color, (c) boldness, or using techniques such as (a) highlighting and (b) animations, marks can be used to convey importance (Tversky, 2011).

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[39]This is especially important since "in principle[,] any signifier could represent any signified" (Chandler, 2017, p. 24). See Figure 5.

[40] Here, I have not included *icons* (also addressed in the literature as pictogram or depictions)—the most popular marks—which are used to convey likeness (Tversky, 2011) because they do not address spatial and temporal arrangements and their meanings do not vary with context. Rather, they are easily recognized which aids in meaning and recollection (Tversky, 2011).

Methodological Groundings

Studies situated in the GT methodology are customarily aligned to one of the numerous methodological variations—classic, Straussian, and CGT—based on the use of relevant literature, the researcher's philosophical view/position (Aldiabat & Le Navenec, 2018; Kenny & Fourie, 2015; Easterby-Smith et al., 2002; Edmondson & McManus, 2007; Saunders et al., 2009, as cited in Makri & Neely, 2021), coding procedures (Kenny & Fourie, 2015), "the research objective, [and] the resources available" (Easterby-Smith et al., 2002; Edmondson & McManus, 2007; Saunders et al., 2009, as cited in Makri & Neely, 2021, p. 2). Since the aim of studies situated in the classic GT methodology is to create a substantive theory devoid of influence by propositions, it is for this reason theoretical/conceptual frameworks are not extracted from literature to guide the classic GT study as is typical of other qualitative methodologies (Birks & Mills, 2015; Kenny & Fourie, 2015; Makri & Neely, 2021). However, I choose to deviate from this traditional path of qualitative studies anchored by the classic GT methodology for a few reasons and embrace the CGT approach.

First, the multiple theoretical/conceptual frameworks that I bring to bear are the cognitive products of the constructivist/constructionist paradigmatic stance that I will use to view the central phenomenon—science teachers' thought processes in interpreting students' scientific models (Anfara & Mertz, 2015; Merriam, 2007). Therefore, I will borrow their concepts, terms, theories, assumptions, and definitions (Aldiabat & Le Navenec, 2018; Anfara & Mertz, 2015; Merriam, 2007; Repko & Szostak, 2021) to initially guide my data collection—using purposeful sampling, snowball sampling, and theoretical sampling—and data analysis (Mason, 2018; Schultz, 1988, as cited in Merriam, 2007)—using in vivo coding (Carmichael & Cunningham, 2017; Kenny & Fourie, 2015), found poetry, reflective and reflexive memos, and diagrammatic displays. However, ultimately, my CGT construction will be informed by the analysis of my data (Mason, 2018). Importantly, these frameworks have also influenced the generation of the research questions (Schultz, 1988, as cited in Merriam, 2007) that are being investigated.

Second, in my study, I perceive a "*theory* as a unique way of perceiving reality, an expression of someone's profound insight into some aspect of nature, and a fresh and different perception of an aspect of the world" (Silver, 1983, as cited in Anfara & Mertz, 2015, p. 14). Thus, I believe the selected theoretical/conceptual frameworks—DMT, VST, and CST—in their collective form will provide a unique and fresh way of examining science teachers' thought processes when interpreting students' scientific models.

Third, I assume that the selected theoretical/conceptual frameworks point to invisible influences on the intangible (Kincheloe et al., 2012, as cited in Jones et al., 2014; Lincoln & Guba, 2013) but relevant thought processes (Clark & Peterson, 1986) involved in the interpretation of students' scientific models. As a systems thinker (Boyatzis, 1998), I understand that multiple processes—in/visible—can inter/act and impact how science teachers interpret students' scientific models.

In keeping more closely with the spirit of CGT methodology, I choose to adopt a balanced approach (Kenny & Fourie, 2015) or a balanced axiological filter (Kivunja & Kuyini, 2017) to integrate the literature in the dissertation. In adopting this approach, I am inspired by and thus adhere to the literature integration recommendations of Charmaz as cited in Kenny and Fourie (2015). Specifically, I have amassed the literature review in its own section as well as other relevant sections in other chapters. To foster creativity and openness, I choose to delay the writing of a comprehensive literature review until the data collection and analysis are completed. A conceptually similar recommendation has been made by Jones et al. (2014). As Jones et al.

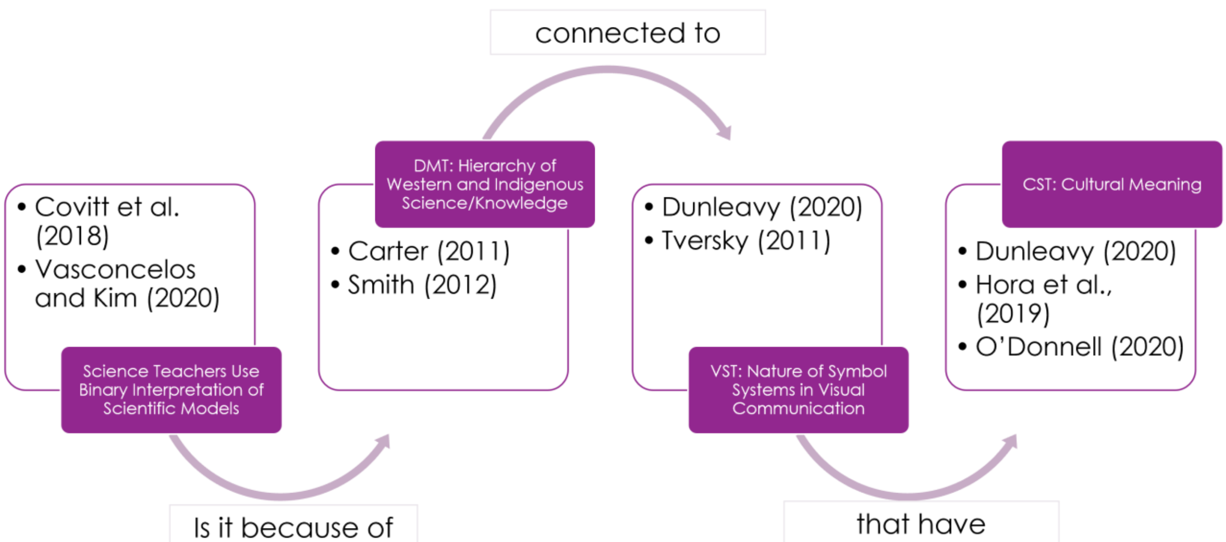
(2014) note, a balanced axiological filter supports the use of a priori theoretical/conceptual frameworks—establishing a balanced theoretical sensitivity—to reveal emerging categories but cautiously recognizes the "need to not constrain possible new interpretations as a result of having this previous knowledge" (Jones et al., 2014, p. 161). I also recognize that leveraging relevant literature "can expedite the conceptual integration needed for theoretical saturation" (Martin, 2019, p. 227). Thus, in employing a balanced axiological filter, I will leverage the selected theoretical/conceptual frameworks to uncover the thought processes of secondary school science teachers and bring transparency to their microsystem, mesosystem, and macrosystem interactions since seminal research (Clark & Peterson, 1986) asserts that teachers' thought processes affect their pedagogical decisions and are therefore consequential.

Developing My Theoretical/Conceptual Framework

Currently, science education literature shows that there is a lack of studies that delineate the processes by which secondary science teachers interpret students' scientific models. Few studies (Covitt et al., 2018; Vasconcelos & Kim, 2020) have acknowledged the elusiveness of the thought processes utilized by science teachers interpreting students' scientific models, in addition to science teachers' binary interpretation of students' scientific models. However, these post/positivist researchers failed to address the cause of the binary interpretation in science education. Serving as a preliminary literature review through which I could visualize and make sense of the research topic, I have brought to bear DMT, VST, and CST as illustrated in Figure 3. Collectively, these theories will help me to notice attributes of culture such as social norms/conventions/rules that are deeply ingrained in the science teachers' instructional practices that are often overlooked by the science teachers (Fourie, 2021). Although these three theories allow me to express my current understanding of the research terrain/ecosystem, I recognize that as a reflexive researcher looking forward, my perception of how science teachers interpret students' scientific models will evolve as my understanding of their thought processes changes (Ravitch & Carl, 2019). What this means is that throughout the research process, I am invariably re/shaping or re/developing[41] (Reichertz, 2019) my understanding of the science teachers' thought processes when they interpret students' scientific models.

Figure 3

Theoretical Framework Graphic



As a social justice theory (Sandel, 2010; Yin, 2018) addressing issues of equity and power (Esposito & Evans-Winters, 2021; Smith, 2012), DMT posits an asymmetrical (Carter, 2011) and binary (Smith, 2012) status between Western/Eurocentric/U.S.-centric/Cartesian knowledge/science and non-Western/Indigenous/other-than-Cartesian knowledge/science which results in the otherization of non-Western/Indigenous people and hegemony of Western/Eurocentric/ U.S.-centric/Cartesian culture within the history of coloniality (Carter,

[41] This re/developing is a product of the abductive inference process (Reichertz, 2019).

2011; Smith, 2012; Walter & Walsh, 2018). DMT makes visible (Walter & Walsh, 2018) the plurality of knowledge, multiple existences (Carter, 2011), distinct perspectives (Walter & Walsh, 2018), and the recognition of power entrenched in this asymmetrical and binary relationship (Carter, 2011; Smith, 2012; Walter & Walsh, 2018). In addition, DMT metaphorically displaces the realist ontological perspective of Western thought as the only lens for viewing the world and recognizes the multiple/subjective perspectives of those considered insignificant (Walter & Walsh, 2018).

In her influential work on DMT, Smith (2012) offers a possible explanation for science teachers' binary interpretation of students' scientific models. According to Smith (2012), the binary interpretation stems from academic/science research during colonialism which created a hierarchical relationship between Western/Eurocentric/Cartesian[42] knowledge and non-Western/Indigenous/other-than-Cartesian knowledge. In her study, Smith (2012) focuses on equity and appropriation issues and shows how Western knowledge/science is inseparable from colonial history and violence. In the project, Smith's (2012) work plays a pivotal role because it connects binary thinking to academic/science research during colonial history which led me to Carter (2011).

Using a similar line of view, Carter (2011) also takes into account the binary interpretation in science education. Like Smith (2012), Carter (2011) points to the historical tradition of assigning a superior hierarchical status to Western/Eurocentric knowledge/science and inferior status to non-Western/Indigenous knowledge/science. In the context of science education, Carter (2011) acknowledges the need for/relevance of multiple epistemologies

[42] Here, I have deliberately dropped U.S.-centric from the compound expression since this is not the focus of Smith (2012).

resulting from multiple existences since globalization has caused a shift from the hegemonic model to include non-Western/Indigenous/Ethno/sciences and Indigenous/local knowledge. Where Carter (2011) deviates from Smith (2012) is that she connects this asymmetrical relationship to semiotics entrenched in colonialism. To gain a deeper understanding of semiotics, I conducted additional literature searches on semiotics which led me to VST.[43]

The VST—a type of linguistic theory (Dunleavy, 2020)—postulates that visual messages such as sketches, diagrams, or drawings are encoded by sign (Dunleavy, 2020) or symbol (Tversky, 2011) systems. Interpretation of sign/symbol systems is based on the 4Cs: cultural practices/habits (Dunleavy, 2020; Tversky, 2011), content expertise, context, and cognitive abilities (Tversky, 2011). In addition, VST suggests that meanings or kinds of knowledge derived from sign/symbol systems are multiple and flexible (Tversky, 2011).

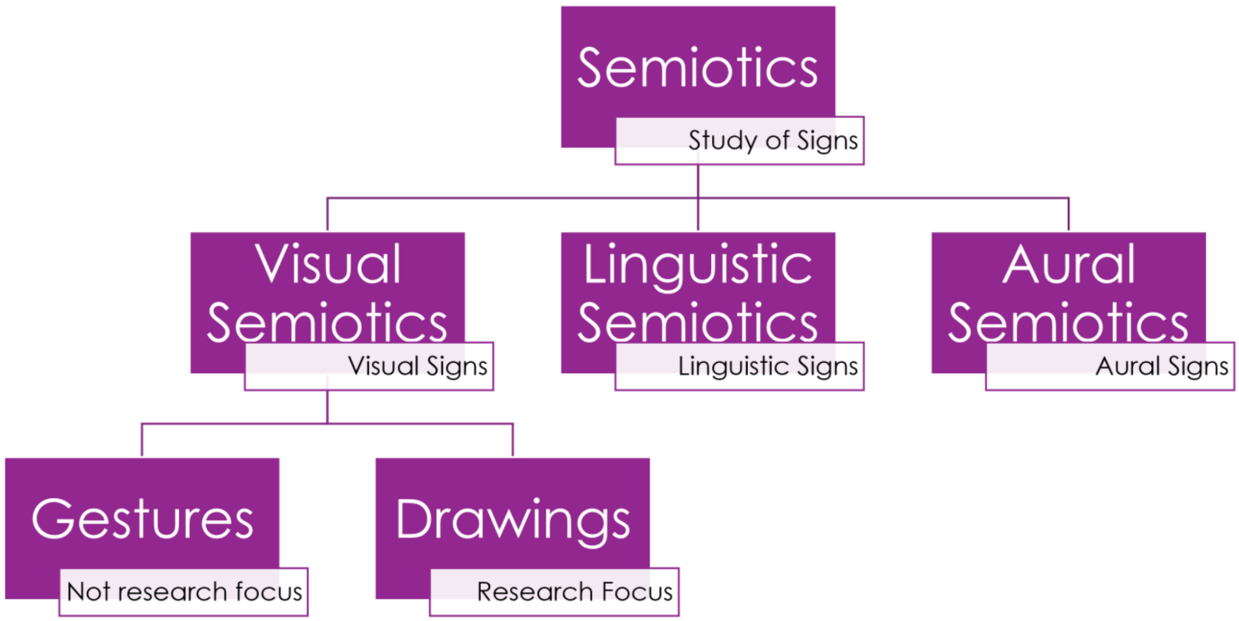
A seminal study on VST from Tversky (2011) broadly addresses the nature of semiotics in various symbol systems such as languages, gestures, sketches, and diagrams. See Figure 4 for a further description of semiotics. Tversky (2011) accounts for cultural differences in the perception of motion in a study with a science education focus. However, these differences are linked to the cultural practices/habits of reading and writing directions, instead of drawing as is the case in my study. She also acknowledges the influence of the 4Cs—cultural practices/habits, content expertise, context, and cognitive abilities—in interpreting sign/symbol systems. In addition, Tversky (2011) invariably studies students' construction or interpretation of symbol

[43] Since drawings are types of visual models, see Figure 4, I selected VST as an appropriate framework from which I could borrow sensitizing concepts (Aldiabat & Le Navenec, 2018) to guide my investigation.

systems instead of the perspectives of teachers, who would have more content expertise than students.

Figure 4

Model of Types of Semiotics

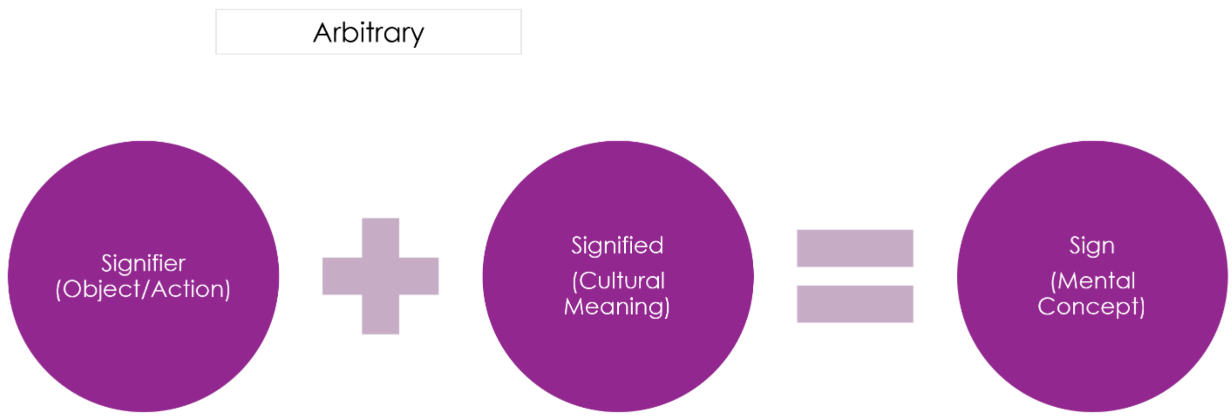


Note. Created from the literature review on semiotics.

In a recent work to address VST, Dunleavy (2020) underscores that signs have hidden meanings that are formulated, negotiated, and shared in cultures. Meaning, Dunleavy (2020) continues, does not reside in the semiotic organization, but rather, it is a product of peoples' actions toward what the symbols represent. Symbols—a class of signs—have culturally assigned meanings. Importantly, the cultural meaning is often arbitrary and depends on how the individual interprets it. See Figure 5. Dunleavy (2020) differs from Tversky (2011) by emphasizing and prioritizing the relevance of the arbitrary and subjective nature of cultural meaning over meaning derived purely from the semiotic organization of systems and phenomena.

Figure 5

Conceptual Model of Signs



Note. Created from the literature review of visual semiotics based on the Saussurean dyadic model of signs.

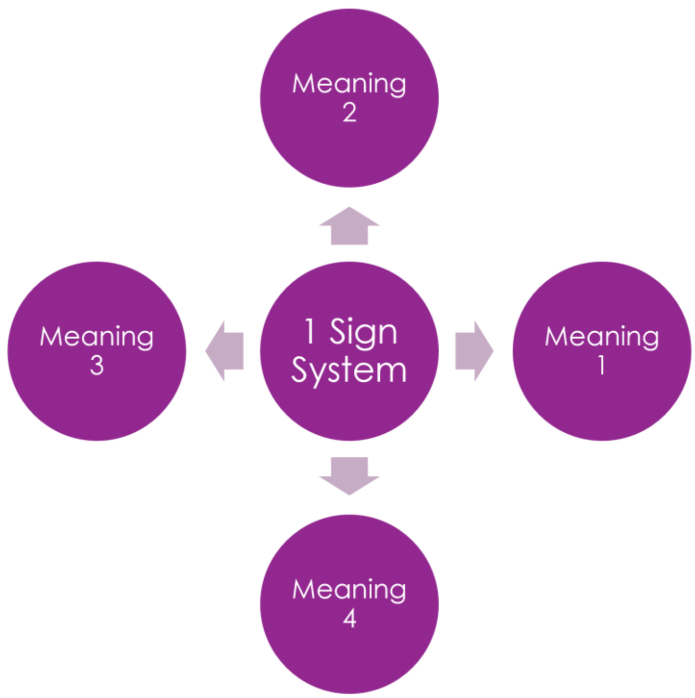
Like VST, CST—a type of group theory (Yin, 2018)—proposes that multiple meanings or kinds of knowledge (Gergen, 2015; O'Donnell, 2020; Tversky, 2011) can be derived from a single representation (Gergen, 2015; O'Donnell, 2020). CST shares with VST the principle that our interpretation of symbols is based on our cultural experiences (Dunleavy, 2020; O'Donnell, 2020; Tversky, 2011). Thus, both theories recognize and promote cultural subjectivity (O'Donnell, 2020) of interpretation. This cultural subjectivity accounts for a plurality of knowledge. Moreover, CST also asserts that membership in the same community or culture results in a common interpretation. Conversely, outsiders lacking the cultural experience would possess an alternative interpretation.

A current study on CST from O'Donnell (2020) acknowledges the polysemic nature of individual signs/symbols and representations. See Figure 6. O'Donnell (2020) agrees with

Dunleavy (2020) and Tversky (2011) that culture plays a role. As a cultural studies theorist, O'Donnell (2020) privileges culture and prioritizes the social construct as the primary factor in interpreting sign/symbol systems. Like Tversky (2011), O'Donnell (2020) recognizes the secondary roles of context and cognitive abilities of the viewer in interpreting images.

Figure 6

Conceptual Model of Polysemic Nature of Signs



Note. Created from the review of the literature on cultural studies and visual semiotics.

A relatively recent CST study, Hora et al. (2019) explore the role of cultural factors in shaping communication in STEM professions—engineering and nursing instead of STEM secondary instruction. Unlike Tversky (2011) who focuses on cultural influence in visual communication genres, Hora et al. (2019) addressed cultural influence on oral communication genres. Like Carter (2011) and Smith (2012), Hora et al. (2019) recognize that scientific disciplines have communicative norms that inform how members construct, interpret, and ascribe meaning to events, tasks, and situations that can be aligned to existing types of cultural models. See Shore (1996) for existing cultural models.[44] These cultural models have the power to determine what gets counted as ab/normal (Foucault, 2007; Foucault et al., 1997; Hall, 1997; Newman, 2016; Smith, 2012). Hora et al. (2019) argue that membership/entry into disciplinary and professional groups requires the enculturation of the norms, languages, and practices.

Thus, in interpreting students' scientific models—a written/visual form of communication, I believe that secondary science teachers are looking for evidence of enculturation of these discipline norms (i.e., "canonical knowledge, techniques, and values") (Aikenhead & Elliott, 2010, p. 322) in students' scientific models that are interpreted as right. This evidence would tacitly manifest itself in the semiotic organization of students' scientific models. I believe that a lack of enculturation of these discipline norms results in teachers interpreting students' scientific models as wrong. In interpreting students' scientific models, science teachers serve as judges who give "an assessment of normality and a technical prescription for a possible normalization" (Foucault, 2007, p. 21). Operating below the radar, these power dynamics ostensibly appear trivial but should be pointed out and critiqued (Gergen, 2015; Robson & McCartan, 2016; Schwan & Shapiro, 2013) despite acting both coercively and productively[45] in getting outsiders to socially conform (Foucault, 2007; Schirato et al., 2020; Schwan & Shapiro, 2013) to "culturally approved directions and by punishing known violations" (Nanda, 1987, as cited in Rhee, 2002). Therefore, having a greater insight into the power

[44] These details of existing types of cultural models are beyond the scope of this paper and the reader is directed to Shore (1996) for more information.
[45] Here I address the 2nd of 4 principles of power according to of power according to Foucault (Schirato et. al., 2020).

relations that shape students' behaviors (Foucault, 1980g, as cited in Taylor, 2014) which are usually based on norms/values/disposition/practices (Schirato et al., 2020) of "white, heterosexual, middle-class…male[s]"[46] would yield useful information about science instruction and assessment (Newman, 2016, p. 18). Thus, my study will bridge the gap by also identifying the disciplinary norms for scientific modeling in secondary science education.

In my study, I seek to bridge this gap or provide a common ground (Repko & Szostak, 2021) by identifying the processes involved when science teachers use binary interpretations of students' scientific models. In these invisible thought processes, in what ways do cultural habits, beliefs, and or practices contribute to binary interpretations? Repko and Szostak (2021) advocate for the use of a common ground approach "when people take opposing positions on a particular issue stemming from conflicting assumptions or values" (p. 272). The specific common ground approach that I will adopt is the technique of transformation. According to Repko and Szostak (2021), *transformation* is used as a common ground technique "when authors make opposing assumptions" (p. 279). I believe that the common ground technique of transformation supports the GT methodology. Like GT, transformation examines opposing categories along a continuum (Repko & Szostak, 2021). GT recognizes that the continuum consists of various stages, steps, or phases (Creswell & Poth, 2018).

[46] Feminist theorists (Alcoff & Potter, 1993) have historically recognized the power in the social status and the sexed-body of the knower in re/shaping our dominant knowledge systems and has called for the reconstruction of epistemology largely influenced by androcentrism. It is through recognizing, pointing out, and dismantling these hierarchies that society can "valorize some of the most discredited perspectives of knowledge" (p. 5). Therefore, the misconception that the androcentric dominant account is objective and free from the social situations of the knower is an epistemologically compromised argument (Harding, 1993). See also Snively and Corsiglia (2001).

In establishing a common ground using transformation or generating the GT, I believe that DMT is bound to be relevant in interpreting the data because it accounts for the perpetuating binary interpretation through its documentation of the historical tradition of colonial practices that privilege Western/Eurocentric culture over the other non-Western/Indigenous culture (Carter, 2011; Smith, 2012). In addition, DMT provides the cultural lens[47] for recruiting a dense sample of participants—that is, participants who possess the knowledge and experience to generate rich data (Aldiabat & Le Navenec, 2018). I also believe that VST is just as relevant because static drawings are visuals that are comprised of signs/symbols whose meanings are multiple and flexible (Spencer, 2010; Tversky, 2011). In this study, VST provides sensitizing concepts[48]—signs/symbols—which guide the researcher in an initial direction in which to look (Aldiabat & Le Navenec, 2018; Rossman & Rallis, 2017). In revealing that culture is the shared knowledge among members of a community, I believe CST is the bridge that unites DMT and VST which makes the culture the context of my study.

Summary

In a review of the interdisciplinary literature, the body of scholarship shows that sources of tension or conflict among the subdisciplines as examined by their theories are caused by differences in philosophical assumptions based on ontology, epistemology, and axiology. This

[47] In designing the survey for recruiting a dense sample of participants, the criteria of non-Western/Indigenous and Western/Eurocentric cultures are adopted from seminal work in the field.

[48] While VST provides sensitizing concepts (Aldiabat & Le Navenec, 2018) to initially guide the data collection and analysis, as a constructivist/constructionist, I will invariably employ abductive approaches (Bryant & Charmaz, 2019; Shank, 1993, November; Tavory & Timmermans, 2014, 2019; Timmermans & Tavory, 2022) to remain flexible to new interpretations that re/shape my understanding of the phenomenon.

interdisciplinary literature divides into several types of studies with themes that include binary interpretation in science education, factors that influence the interpretation of sign/symbol systems, and the cultural meaning of sign/symbol systems. My study will bridge the gap by also adding to the overall literature on science education by integrating the literature (Repko & Szostak, 2021) via constructing a CGT that explains the reason for this binary action while studying the thought processes of science teachers. In doing so, my CGT will connect theories and their associated subdisciplines that are epistemologically distant/close and perhaps feed back into various theoretical/conceptual frameworks (Repko & Szostak, 2021).

CHAPTER 3: METHODOLOGY

In this chapter, a comprehensive description of the research methodology is provided as a rationale for the generation of the research questions, participants' selection, data collection instruments, and data analysis measures. In addition, the chapter also addresses other components of qualitative research which are equally relevant to the research design, specifically, issues of trustworthiness, ethics, and limitations.

Nature of Grounded Theory Methodology

> As an exploratory [methodology], grounded theory is particularly well suited for investigating social processes that have attracted little prior research attention, where the previous research is lacking in breadth and/or depth, or where a new point of view on familiar topics appears promising. (Salkind, 2010, p. 548)

Primarily, GT is used to develop a substantive theory (Bryant & Charmaz, 2007, as cited in Chun Tie et al., 2019; Jones et al., 2014; Kenny & Fourie, 2015) for a "process or an action that has distinct steps or phases that occurs over time" (Creswell & Poth, 2018, p. 83) and has a progression or pathway (Harley et al., 2009) that need to be figured out. A preliminary theory is widely acknowledged as a model (Frigg & Hartmann, 2020) or framework (Harley et al., 2009). In other words, the previously identified distinguishing factor can be summarized as a model/theory/framework produced from GT methodology should be employed to identify and visualize phases, stages, or steps to create a progression or pathway for a question that addresses a process or action of the participants. Charmaz (2020) clarifies that GT facilitates visualizing "connections between…meaning and actions[49]…that otherwise may remain invisible" (p. 167).

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[49] Therefore, as a researcher, I am treating the actions of teachers as signs, from which I will generate interpretation(s) as will be illustrated in the CGT (Chandler, 2017).

However, the theory that is generated is substantive and not formal (Charmaz, 2020; Creswell & Poth, 2018; Jones et al., 2014). As a substantive theory, a GT is not generalizable to the population (Charmaz, 2014, as cited in Birks & Mills, 2015; Creswell & Poth, 2018; Charmaz, 2006, as cited in Jones et al., 2014). Often displayed as diagrams (Creswell & Poth, 2018) or illustrative models (Birks & Mills, 2015) in numerous studies, the findings in GTs can also be represented as discussions (Creswell & Poth, 2018).

For four reasons, GT is well-suited as the methodology for this study. One, as an exploratory methodology that is useful for studying unexplored areas of research (Chun Tie et al., 2019; Robson & McCartan, 2016; Salkind, 2010), GT will shed light on this neglected area in scientific model research. Two, as a methodology that can aptly visualize stages, changes, and processes over time (Creswell & Poth, 2018), GT is a consummate match for studying the processes that science teachers use in interpreting students' scientific models. Three, these stages, changes, and processes involved progressions or pathways that needed to be figured out (Harley et. al., 2009). Four, as unobservable processes (Charmaz, 2020) that occur in the heads of teachers (Clark & Peterson, 1986), GT is also a productive way for studying and connecting the meaning to these invisible actions (Charmaz, 2020) that comprise the thoughts of science teachers when they interpret students' scientific models.

A Rationale for Selecting Constructivist Grounded Theory

Having provided a rationale for the use of GT methodology in the previous section, I provide a more concrete overview of the CGT methodology that I invariably use in this work. As stated in the section addressing situating the study as a CGT in Chapter 1, I believe in multiple realities and multiple kinds of knowledge/truths/meanings. In addition, guided by these ontological and epistemological views, I choose to move away from both the classic and Straussian methodological approaches for my research.

Philosophical Positioning. Although Glaser—the pioneer of classic GT—is reticent in positioning this methodological variation as positivist, Charmaz (as cited in Kenny & Fourie, 2015)—a former student—suggests that classic GT is anchored by positivism because of tacit assumptions of objective epistemology, external/naïve realist ontology, fixation on a neutral and logical researcher who discovers an emergent GT.

Although there are acknowledgments that the positivism classification of the classic GT is warranted, disagreements in the literature exist. While other researchers (McCann & Clark, 2003; Urquhart, 2002, as cited in Kenny & Fourie, 2015) disagree with Charmaz's classification of the classic methodological variation as being positivist and suggest a postpositivist classification based on critical realist ontology—limitations of the researcher in interpreting reality—I have repudiated this alternative explanation since Glaser's article *Constructivist Grounded Theory?* acknowledges Charmaz's claim of classic GT having an external ontology and independent researcher.

Similarly, Charmaz (as cited in Kenny & Fourie, 2015) also notes that the Straussian methodological variation is entrenched in the positivism paradigm as is evident in assumptions of external/objective ontology and precise methodological procedures. It is these positivist assumptions that create tension with my constructivist/constructionist paradigm.

Supported by my literature search, I have a few other motivating reasons for adopting a CGT methodology. From the review of Charmaz (2016) and Charmaz (2020), these salient points that are described below are relevant to my study since collectively, their presence adds a notable advantage/strength/credibility/transparency to my study. One of the most powerful features of the CGT methodology is that reality and truth are perceived as fluid. The remarkable feature of this presupposition is that in interpreting the symbols that comprise students' scientific models, I believe that the ontological perspective of the observed/participants impacts the interpretation. Another core feature of the CGT methodology is that it compels the researcher to engage and develop her methodological self-consciousness—to reflexively gaze inward and outward. As a researcher that leverages the reflexive tools of the CGT methodology, I was invariably questioning and scrutinizing my positions, privileges, and priorities and how they impacted the research design and my relationship with the participants. Specifically, as a Black woman who is a member of two elite groups of science teachers—the New York State Master Teacher Program (NYSMTP), and the Science Teachers Association of New York State (STANYS)—I used my position and privilege as a science master teacher to recruit participants. However, in writing this study, I constantly questioned if my doctoral priorities of obtaining results that could potentially reveal issues of power jeopardize my relationships within these networks of science teachers. "[Power] is everywhere and always alert, since by its very principle it leaves no zone of shade" (Foucault, 2007, p. 177). But, pretending that these power differentiations across cultures do not exist "inadvertently maintain the status quo under the guise of *mutually beneficial* (Coburn et al., 2013) partnerships"(Esposito & Evans-Winters, 2021, p. 14).

As a Black qualitative researcher with a seat at the research table, I want my dissertation to contribute to educational transformation (Esposito & Evans-Winters, 2021). Therefore, choosing the safe path deviates from the kind of research I want to produce and the goals that I desire to accomplish (Fourie, 2021). Thus, to reconcile my decision, I turned to CGT scholarship for advice since "[CGT] provides tools for studying power" (Charmaz, 2016, p. 12). To better understand science teachers' thought processes in interpreting students' scientific models that are comprised of drawings, CGT also advocates for looking forward and backward into an issue using analytic tools such as the abductive approach—generating the most plausible explanation for unique/surprising/unexpected/anomalous/serendipitous observations[50] (Reichertz, 2019; Shank, 1993, November; Tavory & Timmermans, 2014, 2019; Timmermans & Tavory, 2022). For my study, the most plausible explication was one that identified the thought processes that explain the surprising claim from an extant study (Vasconcelos & Kim, 2020)—science teachers' binary interpretation of students' scientific models. In my study, generating the most plausible explanation met the criterion of looking forward, the use of extant research served as the baseline, and the chosen theoretical frameworks met the criterion of looking backward.

Flexibility of Coding Procedures. Unlike the classic GT and Straussian GT, the CGT brings to bear flexibility in coding procedures that is lacking in early methodological variations. Specifically, the Straussian variation offers a detailed, complex "rule-bound, prescriptive approach…[which] stifles and suppresses the researcher's creativity" (Kenny & Fourie, 2015, p. 1278). In the Straussian variation, the researcher must engage in (a) open coding, (b) axial coding, (c) selective coding, and (d) conditional matrix prior to generating the GT. Similarly, other rigid requirements are integrated within the classic GT methodology. The use of a large breadth of data to correct for theoretical and paradigmatic orientations is an illustrative example of these inflexible expectations (Kenny & Fourie, 2015). As a constructivist/constructionist

[50] Importantly, these "[s]urprises are the fuel that powers research engine" (Timmermans & Tavory, 2022, p. 1) in creating a new theory. As Timmermans and Tavory (2022) reveal, during data collection, this can be accomplished "by adding a site as a comparative case" (p. 9) such as the use of five schools as is the case of my study.

researcher with limited access to available resources, whose objective is to develop an exploratory GT, the flexibility of the constructivist methodology seems like a consummate match for my study.

Research Questions

Since the purpose of a CGT study is to develop a theory for a "process or an action that has distinct steps or phases that occurs over time" (Creswell & Poth, 2018, p. 83), I had purposefully phrased my investigatory questions to identify and describe the thought processes of science teachers in interpreting students' scientific models. Thus, the methodology shaped the subsequent two qualitative research questions:

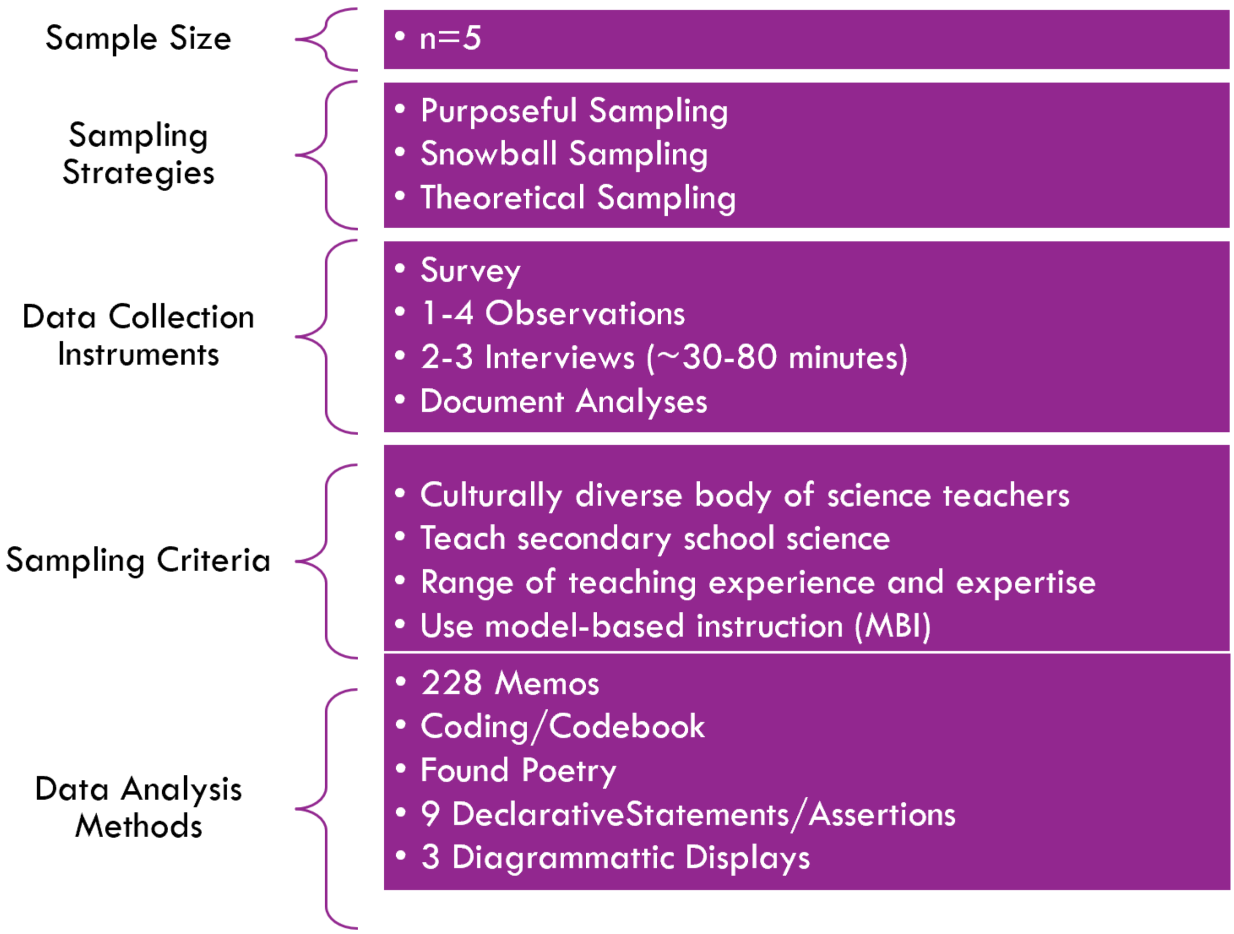
1. What are the thought processes used by secondary science teachers in interpreting students' scientific models that are comprised of drawing activities?
2. In what way does culture play a role in secondary science teachers' thought processes when interpreting students' scientific models that are comprised of drawing activities?

Research Design

Since the variables/categories responsible for secondary science teachers' interpretation of students' models were unknown, qualitative data collection instruments and data analysis methods were needed (Creswell & Creswell Báez, 2021) as illustrated in Figure 7.

Figure 7

Procedural Model of Research Design



Participants

To facilitate the identification of the categories and themes from rich data, I used three sampling techniques: purposeful sampling, snowball sampling, and theoretical sampling. I employed purposeful sampling to recruit a diverse body of science teachers with shared expertise (Carmichael & Cunningham, 2017) or experience (Boddy, 2016; Charmaz, 2006, as cited in Jones et al., 2014) about scientific models and how they are interpreted to better understand this central phenomenon. See Table 1: Participant's Profile. When it became challenging to recruit participants with these essential characteristics of the study, I employed snowball sampling by asking participants to recommend colleagues who fit the participant's profile or conceptual frameworks of the study (Saldaña & Omasta, 2018). Unique to GT methodology, theoretical sampling was employed near the final stage of data collection until theoretical saturation was achieved which "is a necessary factor in the integration of the final theory" (Birks & Mills, 2015, p. 96). This means that I collected and analyzed data until I could identify the stages[51] in the science teachers' thought processes and could construct an explanation for the identified stages (Mason, 2018). Recognizing the three-component approach to theoretical sampling, I integrated the transcripts, the codes, and the concepts from the literature (Carmichael & Cunningham, 2017). In searching for theoretical saturation, when a negative/contradictory case surfaced, I compared the difference to the saturated sample and adapted the CGT accordingly (Mason, 2018) using abductive reasoning (Reichertz, 2019; Shank, 1993, November; Tavory & Timmermans, 2014, 2019; Timmermans & Tavory, 2022). More specifically, I used the negative case to highlight alternative/multiple viewpoints in the theory (Shank, 1993, November; Tavory & Timmermans, 2014, 2019; Timmermans & Tavory, 2022). To decipher these alternative/multiple viewpoints of an inchoate theory (Fourie, 2021), I blended both semiotic and abductive approaches (Shank, 1993, November) to determine "[w]hat [are these] cases of?" (Tavory & Timmermans, 2019, p. 532). In other words, was I witnessing cases of "cause and effect[?], or… [were they] similar to others already experienced and explained [?]" (Tavory & Timmermans, 2019, p. 537).

[51] For each stage, the goal was to construct a data set─as evident in the codebook─that exemplify a typology (Timmermans & Tavory, 2022).

Table 1

Participants' Profile

T#	Topic(s) Observed	Ethnicity	Gender	MBI	Context	Race	Discipline	Language(s)	Drawing
1	Circuits	Not Hispanic or Latino	F	>20yrs	Summer Camp	Asian	Physics	English	[a]Low-Fidelity Static
2	Particle diagrams, chemical reactions, and electrochemistry	Not Hispanic or Latino	F	>20yrs	Summer High School	Asian	Chemistry	English, Hindi, and Punjabi	Static
3	Hydrogen bonding in water	Not Hispanic or Latino	F	>20yrs	Public High School	Mixed Race	Biology	English	Static
4	Force diagrams: Newton's Laws	Not Hispanic or Latino	M	>20yrs	Public High School	White/American Indian	Physics	English	Static
5	Force diagrams: Newton's Laws and magnetism	Not Hispanic or Latino	F	1-5 yrs	Public Middle School	White	Physics	English	Static

Note: Prepared from the survey data. See Appendix A: Survey Questions. T# is the teacher's identification number. F represents female, and M represents male.

This low-fidelity static drawing consisted of using pen/cil markings on paper with conductive copper tape and several light-emitting diodes (LEDs) to construct a paper circuit (Hershman et al., 2018).

In the GT literature, there has been a lack of consensus about appropriate sample sizes in GT studies with several studies suggesting six (Morse, 1994, as cited in Carmichael & Cunningham, 2017), 10 (Sandelowski, 1995, as cited in Boddy, 2016; Saldaña & Omasta, 2018), 20 to 30 (Creswell & Poth, 2018), 20 to 35 (Kuzel, 1992, as cited in Carmichael & Cunningham, 2017), 30 (Makri & Neely, 2021), and 15 to 60 (Saunders & Townsend, 2016, as cited in Carmichael & Cunningham, 2017). Thus, this issue remains open for debate. In light of this information, my choice of sample size was largely inspired by Aldiabat and Le Navenec (2018), Boddy (2016), Carmichael and Cunningham (2017), and Sim et al. (2018). These scholars note that a researcher's choice of sample size is dependent on (a) the scientific paradigm (Boddy, 2016; Sim et al., 2018) or the philosophical underpinnings of the methodology (Aldiabat & Le Navenec, 2018), (b) data saturation (Aldiabat & Le Navenec, 2018; Boddy, 2016; Carmichael & Cunningham, 2017; Sim et al., 2018), (c) experience and expertise of the researcher, (d) appropriately selected participants with the knowledge and experience, (e) multiple interviews with the same participants (Aldiabat & Le Navenec, 2018; Carmichael & Cunningham, 2017), (f) theoretical sampling (Carmichael & Cunningham, 2017), (g) classification of research as exploratory, descriptive, or explanatory (Sim et al., 2018), (h) crystallization/triangulation of data from multiple data collection methods (Aldiabat & Le Navenec, 2018; Rowlands et al., 2016), and (i) budget of the researcher (Aldiabat & Le Navenec, 2018).

Since GT research anchored by positivism requires larger sample sizes (Boddy, 2016), for this CGT study, the participant pool commenced with a relatively small sample size of six,[52] secondary school science educators. Importantly, in studies investigating theoretical saturation,

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[52]As a new researcher, the use of a small N sample allowed me to better understand and interpret the meaning of participants' responses (Timmermans & Tavory, 2022).

Boddy (2016) notes that data saturation became evident with a sample of six participants. Thus, to garner an appropriate sample, I recruited participants that are culturally diverse, teach physical science, have a range of teaching experience, use MBI as an instructional technique, and work in a secondary school setting. The purpose is to “deconstruct… commonly accepted ways of [interpreting scientific models] and [our general] understandings [of them] so that these are not taken-for-granted but are exposed for the extent to which they both influence and are influenced by prevailing ways of thinking” (Robson & McCartan, 2016, p. 39). Therefore, while the actual size was ultimately decided through the process of (a) purposeful sampling, (b) snowball sampling, (c) theoretical sampling, (d) prolonged engagement during each interaction, (e) multiple data collection[53] methods, and (f) experience and resources of the researcher (i.e., time, money, and availability of the participants) to deal with large data sets, etc, to ensure in-depth analysis and rich quality of data within workability/practicality of researcher capacity as a doctoral student with a defined timeline (Aldiabat & Le Navenec, 2018), I did not need to have more than five participants.

Collecting data from a spectrum of varying cultures ensured that data traverse various cultures.[54] Several studies (Carter, 2011; Dunleavy, 2020; O’Donnell, 2020; Smith, 2012; Tversky, 2011) acknowledged that culture has an impact on interpretation. Physical science is the scientific discipline of interest since it leverages semiotic organization to capture low salience and high relevance in demonstrating proficiency in understanding science systems and phenomena. See Figure 2. Scientific model scholarships addressing physical science (Chang et

[53] In the project, multiple data collection methods—surveys, observations, document analyses, and interviews—are brought to bear as addressed in the section data collection methods and analysis.
[54] See Chapter 1: Overview, subsection Cultural Context, paragraph 2 for sensitizing concepts that guide my interpretation of culture for data collection.

al., 2014; Hodgkiss et al., 2018; Mason et al., 2013; Passmore et al., 2017; Wilkerson-Jerde et al., 2015) have documented the proficiency of semiotic organization in capturing low salience and high relevance features of scientific phenomena and scientific systems. Secondary school is the grade band of interest because I am knowledgeable of the curriculum and would be able to leverage this insider access to the curriculum in data collection and analysis. A rich quality of data requires that the selected science teachers have expertise/knowledge in interpreting students' scientific models. Tversky (2011) pointed out the relevance of content expertise in interpreting signs/symbol systems. In this study, expertise/knowledge is operationalized as (a) the integration of MBI in one's teaching repertoire and (b) experience with static drawings since they are the specific type of scientific models that are the emphasis of my project.

This initial sampling frame was highly narrow and became impractical during implementation in the field (Mason, 2018). Since the sampling frame was very narrow, my contingency plan involved widening the sampling frame to include participants that use drawing activities that are dynamic and work in all science domains (Mason, 2018). However, I believe that these sampling modifications still targeted the central phenomenon of exploring the thought processes of science teachers when interpreting students' science models. In addition, scientific model scholarships (Chang et al., 2014; Wilkerson-Jerde et al., 2015) have also documented success with dynamic drawings in the interpretation of the thought processes of students.

To better understand my central phenomenon, I also listened to the voice of the science teachers—the researched/the Other—observe their actions, reactions, interactions, routines, rituals, and rules to discern the in/visible meanings (Jones et al., 2014; Saldaña & Omasta, 2018) concerning interpreting students' scientific models instead of relying on my preconceptions—the researcher/the self (Jones et al., 2014). In addition, I analyzed the curriculum resources, specifically textbooks, diagram-based electronic resources, and students' models since these "visually empirical materials…are inseparable parts of [the setting]" (Saldaña & Omasta, 2018, p. 103). That is, ownership makes them extensions of the science teachers' identity (Saldaña & Omasta, 2018).

Data Collection Methods and Analyses

Several data collection methods—survey, observation, artifact/document analysis, and interviews—were employed in this CGT study. I believe each method highlighted a different aspect of the science teachers' thought processes and collectively, provided a deeper understanding of the stages in the processes (Mason, 2018). The order of appearance—survey, observation, artifact/document analysis, and interviews—for the data collection methods was significant since the information gathered from the previous method(s) was leveraged to maximize data collection from the participants in the subsequent method(s). Though the inclusion of surveying does not strictly adhere to the conventional data collection methods of qualitative research, I included this method because I believed that it would aid in the generation of insightful and rich data (Mason, 2018).

Survey. Using an online survey, participants were recruited from a district in lower New York State and the STANYS network. As a member of these communities of science educators, I believe membership justifiably gave me insider access to the gatekeepers to facilitate recruiting participants. The survey was distributed and analyzed to facilitate purposeful sampling of participants who have knowledge of the "behaviors, feelings, actions, or reactions" (Jones et al., 2014, p. 147), experience (Boddy, 2016; Charmaz, 2006, as cited in Jones et al., 2014; Tversky, 2011), and expertise (Carmichael & Cunningham, 2017) that applies to the phenomenon of scientific modeling/drawings. Specifically, the survey was initially analyzed to identify science teachers that are culturally diverse, teach physical science/topics, have a range of teaching experience, use MBI as an instructional technique, and work in a secondary school setting. See Appendix A: Survey Questions.

Observation. From the survey, six participants (Creswell & Poth, 2018; Saldaña & Omasta, 2018) were selected. However, only five participants were used for a series of approximately one to four a/synchronous observations to crystallize the data (Tracy, 2010) and facilitate data saturation[55] (Aldiabat & Le Navenec, 2018), keeping in mind "[t]he challenge[s in] determining the degree of observation and participation appropriate to address the research question while maintaining ethical obligations to the participants" (Jones et al., 2014, p. 142). Taking an active role as a researcher (Saldaña & Omasta, 2018), I observed science lessons using MBI to examine the manifest cultural knowledge/behavior/actions (Boyatzis, 1998; Kenny & Fourie, 2015; Saldaña, 2016; Saldaña & Omasta, 2018) such as the visual semiotics—specifically, the sign/symbol systems that students and teachers used in constructing scientific models—and latent cultural knowledge (Boyatzis, 1998; Saldaña & Omasta, 2018) such as "rules for thinking" (Nisbett, 2003, p. xv). See Figure 5. I also looked for noncultural knowledge/behaviors/actions (Kenny & Fourie, 2015) that ir/regularly surface (Mason, 2018).

[55] Using the recommendations from Onwuegbuzie and Leach, 2007, as cited in Aldiabat and Le Navenec (2018) to facilitate data saturation in the study, I designed the study to have multiple contacts with each participant (one to four observations and two to three interviews which includes member check and or reflection) and prolong engagement during each interaction (~30-80 minutes).

Using in vivo coding[56] first descriptively (Carmichael & Cunningham, 2017) then with gerunds[57] (Carmichael & Cunningham, 2017; Charmaz, 2020; Kenny & Fourie, 2015) or process coding (Carmichael & Cunningham, 2017; Kenny & Fourie, 2015; Saldaña, 2016; Saldaña & Omasta, 2018) to maximize the yield of rich data (Carmichael & Cunningham, 2017), observations were analyzed to identify the meaning that the teachers and students assigned to these non/cultural content using dual reflection models: "'what?' 'so what?' 'now what?'" (Carmichael & Cunningham, 2017, p. 62)…[and] a micro-, meso-, macro- framework (Lipp, 2007, as cited in Carmichael & Cunningham, 2017; Saldaña & Omasta, 2018).[58] In this CGT study, data collection and analysis using the observation method were inductive (Birks & Mills, 2015; Creswell & Poth, 2018; Saldaña, 2016; Saldaña & Omasta, 2018), concurrent/simultaneous (Birks & Mills, 2015; Creswell & Poth, 2018; Jones et al., 2014; Saldaña, 2016), and iterative processes (Birks & Mills, 2015; Charmaz, 2020; Creswell & Poth, 2018; Saldaña, 2016; Saldaña & Omasta, 2018) that facilitated the generation of codes and eventually categories using the constant comparison method[59] (Aldiabat & Le Navenec, 2018;

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[56] As a CGT researcher, I recognized that multiple coding methods aided in crystallization/triangulation, generation of categories, clarification of meaning within/between categories, and capturing the emic perspective.

[57] For a CGT, gerund or process coding was ideal for investigating actions such as the thinking routines of teachers when they interpret students' scientific models and the stages/sequences involve in those routines.

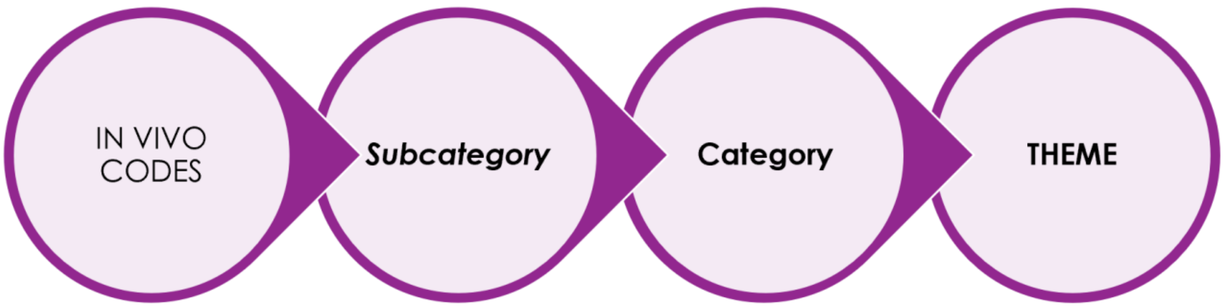
[58] For all data collection methods in the project, I leveraged the 'what?' 'so what?' 'now what?' reflection model to identify the codes, their meanings, and the implications within the context of the study. In addition, I brought to bear the micro-, meso-, macro- framework to examine implications for individual classrooms, school districts, and New York State policies where applicable in the project.

[59] During the constant comparison method, I used the abductive recommendations of Carmichael and Cunningham (2017) to compare new data sets, codes, and categories to existing ones to reflexively look backward to identify "similarities, differences, patterns, relationships, refinements, definitions, dimensions, assumptions, and properties" (p. 62).

Carmichael & Cunningham, 2017; Kenny & Fourie, 2015) to create a "visual model [known as] the axial coding paradigm" (Creswell & Poth, 2018, p. 85). See Figure 8.

Figure 8

Coding Style: In Vivo Codes to Theme



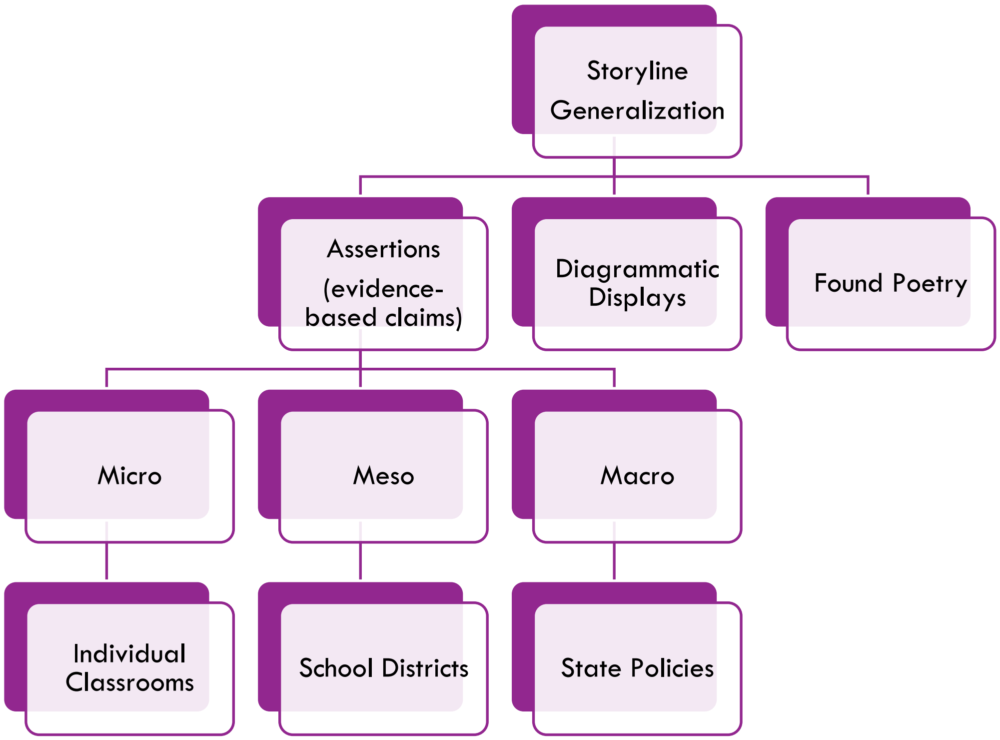
Note. Created from the literature review on styles of coding based on Saldaña (2016) and Saldaña and Omasta (2018)

Though the construction of a paradigm model is typical of the Straussian GT (Kenny & Fourie, 2015), it served as an aid in writing a storyline—the CGT—that interprets the interaction of the categories (Creswell & Poth, 2018; Kenny & Fourie, 2015; Saldaña & Omasta, 2018). See Figure 9.[60] Field notes were recorded using an observation protocol that includes analytical notes for my reflection (Saldaña & Omasta, 2018). See Appendix B: Observation Protocol.

[60] To avoid one of the pitfalls of writing a GT as explicated in the literature (Reichertz, 2019; Tavory & Timmermans, 2019), I leveraged the analytical features of Figure 9 to abductively construct a narrative analysis of the GT that includes how and why relevant themes matter for students, science educators, and policymakers in the field of science education. See Chapter 5.

Figure 9

Model for Storyline Generation



Note. Created from the literature review of data analysis for grounded theory.

Document Analysis. "To confirm other data and expose additional perspectives" (Jones et al., 2014, p. 143) and realities (Rapley, 2018), textbooks and instructional visual ancillaries that participants used for curriculum and instruction were analyzed since extant research (Vasconcelos & Kim, 2020) underscored that they play a relevant role in science teachers' interpretation of students' scientific models. In other words, these visual documents can influence how science teachers think (Rose, 2016, as cited in Jones et al., 2021) and allowed me to develop a deeper understanding of the science teachers' culture (Pauwels & Mannay, 2020, as cited in Jones et al., 2021) since they "uncover behaviors that reveal actual versus professed values and beliefs" (Marshall & Rossman, 2016, as cited in Jones et al., 2021, p. 194). In addition, the multiple perspectives and multiple realities that can be constructed from documents such as textbooks and instructional visual ancillaries also provided an initial direction for analysis in reflexive analytic memos (Rapley, 2018).

In analytic memos, analysis of the multiple perspectives and multiple realities in these documents occurred via the investigation of their manifest and latent content and symbolic meaning (Boyatzis, 1998; Saldaña & Omasta, 2018). The analysis of the manifest and latent content and symbolic meaning were leveraged to generate questions for subsequent semi-structured interviews to determine the role they play in developing the science teachers' "values, attitudes and beliefs" about scientific modeling (Saldaña & Omasta, 2018, p. 105).

Other scholarships (Mason, 2018; O'Donnell, 2020; Rapley, 2018) were leveraged to guide the development of semi-structured questions and tactics for discourse analysis. In analyzing how participants use their documents, Rapley (2018) advocates for generating questions that elicit responses regarding the importance of the textbooks and instructional visual ancillaries to various tasks and situations. Thus, revealing the documents' material culture (Rapley, 2018; Rossman & Rallis, 2017) or cultural repository (Higgins, 2016) which is relevant to participants' actions and discourse.

O'Donnell (2020) proposed several questions for studies involving culture that provided guidance in analyzing documents that contain visuals. Some of these questions were adapted for use in the document analysis section of this study. Specifically, the questions were slightly customized to best address the central phenomenon—scientific models. See Appendix C: Document Analysis Protocol with Visuals. For documents without visuals that have influenced the participants' thought processes as indicated by the participants, an alternative protocol was used. See Appendix D: Document Analysis without Visuals.

To make meaningful comparisons between the two types of documents—documents with visuals and documents without visuals—I analyzed three factors. One, I analyzed the content of the documents for the themes—non/cultural—that emerge (Mason, 2018). Two, I also analyzed the context in which the documents are used by the participants. Specifically, are they used for lesson planning/instruction and or knowledge acquisition of scientific modeling best practices? Three, I analyzed the documents for the "system[/rules] used…[by the participants to] judge their quality" (Mason, 2018, p. 66).

Interview. For in-depth exploration, online/synchronous (Jones et al., 2021) semi-structured interviews were conducted for all participants. While atypical for a GT study (Jones et al., 2014), I employed one semi-structured interview[61] because it provided the latitude to adjust questions in the form of an in-interview analysis (Saldaña & Omasta, 2018). Post-interview, the data consisting of participants' explanatory narration (Lyon, 2020) were concurrently analyzed along with further literature review (Kenny & Fourie, 2015) to make linguistic and epistemological connections (Martin, 2019). Analysis of the participants' explanatory narration offered the best approach to revising the interview questions because it provided the marching orders for selecting subsequent participants (Carmichael & Cunningham, 2017; Timmermans & Tavory, 2022) in a process classified *as sequential interviews*[62] (Timmermans & Tavory, 2022).

Due to the COVID-19 pandemic, interviews were conducted online using Zoom for social distancing and to facilitate the recording of interview data. Having recordings of the

[61] Here, I distinguish the semi-structured interview from the other types of interviews—member check and member reflection—that are integrated in the study which is an approach that is recognized by several scholars (Creswell & Miller, 2000; Jones et al., 2014, 2021; Tracy, 2010).
[62] Though sequential interviewing does not provide a statistical representative sample, this approach offers the best technique to selecting participants base on emerging theoretical grounds (Timmermans and Tavory, 2022).

interviews also provided the opportunity to observe how signs/symbols in the students' models interrelate with the participants' spoken narratives (Lyon, 2020).

The interviews spanned approximately 30 to 80 minutes and appointments were made based on the convenience of the participants (Saldaña & Omasta, 2018). Field notes were documented using an interview protocol to include several open-ended questions to elicit the thought processes that science teachers bring to bear in interpreting students' scientific model, a participant observation activity, and my impression/reflections (Saldaña & Omasta, 2018). The use of open-ended questions allowed for more complex rich responses to emerge (Carmichael & Cunningham, 2017). As a part of the participant observation (Repko & Szostak, 2021) or think-aloud (Clark & Peterson, 1986; Ericsson, 2018) activity, teachers were "asked to perform a task [of interpreting two samples of their students' scientific models][63] and describe verbally their thoughts while doing so" (Szostak, 2004, as cited in Repko & Szostak, 2021, p. 211). According to Ericcson and Simon (1980; as cited in Clark & Peterson, 1986), these types of verbal reports are trustworthy in studying the science teachers' thought processes because participants are "reporting on the contents of short-term memory…[they are] currently attending to" (p. 259). See Appendix E: Interview Protocol. Embedded in the interview process were opportunities for participants to (a) freely share their concerns as long as the revelation was relevant to the research questions (Carmichael & Cunningham, 2017), (b) participate in member checking (Aldiabat & Le Navenec, 2018) of transcripts with evolving codes/themes, (c) respond to clarifying questions that surfaced during our previous data collection encounters, and (d) engage

[63] My decision to use teacher selected models from their own classroom instead of prepared models provided by the researcher is because the former offers "a range of benefits, including a greater degree of participant[s'] intimacy with the [scientific models], a range of different analytical perspectives and the enabling of other relevant meanings to be identified and considered beyond the formal concept being investigated" (Lyons, 2020, p. 301).

in member check and or reflection[64] (Creswell & Miller, 2000; Jones et al., 2014, 2021; Tracy, 2010) of thematic statements/assertions/evidence-based claims and diagrammatic displays.

Establishing Trustworthiness

To ensure that the methodology in my qualitative study is trustworthy, I adopted several of the characteristics outlined by Tracy (2010) as criteria of quality in addressing the participants' selection, data collection instruments, and data analysis methods. These include sincerity, credibility, resonance, rigor, and ethical sensitivity.

The research design showed sincerity in several ways. I overtly expressed my theoretical and paradigmatic orientations in Chapter 1 in the section that situates the study as a CGT. Where applicable in the research design process—selecting theoretical/conceptual frameworks, data collection, and data analysis—I shared my assumptions and how they affect or guide my thinking about the phenomenon. I showed my transparency and self-reflexivity about my data collection methods, data analysis approaches, and challenges via multiple memos.

I showed credibility using numerous techniques. The design used found poetry to show the participant's thought processes instead of telling. Specifically, the rich descriptions were provided by the participant's own words with transitional words meticulously interspersed to create continuity and fluidity. See section: The Thought Processes of Secondary School Science Teachers. I used crystallization via the use of multiple data collection methods (Aldiabat & Le Navenec, 2018)—observation, interview, and document analysis to reveal the multi-dimensionalities (Richardson, 2000b, as cited in Tracy, 2010) of the central phenomenon. For the

[64] A point worthy of emphasis, in this study, the member check and reflection are also classified as interviews.

participants, I used member reflection by sharing the found poetry, nine assertions, and diagrammatic displays with them to see if they were "recognizable to [them] and reflect back to [them]" (Jones et al., 2014, p. 190). In using five participants (Sandelowski, 1995, as cited in Boddy, 2016; Morse, 1994, as cited in Carmichael & Cunningham, 2017; Saldaña & Omasta, 2018), I demonstrate multivocality by using sufficient participants. This approach generated enough data to construct a found poetry, nine assertions, and diagrammatic displays that "bring[s] elements of [data] from different participants" so that the data could not be ethically linked to one participant (Saldaña & Omasta, 2018, p. 270).

Like credibility, I also used found poetry to demonstrate resonance in the study. Through evocative representation accomplished via the found poetry, the voice of the participants will move the reader—especially when paired with the thematic statements/assertions I generated—to see the invisible issues—thus achieving aesthetic merit (Tracy, 2010). See section: The Thought Processes of Secondary School Science Teachers. See also the section: The Role of Culture in the Science Teachers' Thought Processes.

For rigor, I used multiple a priori theoretical/conceptual frameworks (Tracy, 2010) to facilitate purposeful sampling of participants and to reveal emerging categories in the data. In addition, I established rigor through the collection of sufficient data that is expected for the CGT methodology—sampling six participants (Sandelowski, 1995, as cited in Boddy, 2016; Morse, 1994, as cited in Carmichael & Cunningham, 2017; Creswell & Poth, 2018; Saldaña & Omasta, 2018) though needing only five, integrating via crystallization, a variety of qualitative data collection methods—interviews, observations, and document analyses—which resulted in prolonged engagement in the field (Aldiabat & Le Navenec, 2018; Tracy, 2010)—seven months. Another approach I used to establish rigor is being transparent by exercising reflexivity in memo writing about the processes—coding, generation of categories for my codebook, found poetry, thematic statements/assertions, and diagrammatic displays—that I used to transform, organize, and display the data (Aldiabat & Le Navenec, 2018; Tracy, 2010). This showed how I worked with emerging and inductive approaches for data collection and analysis and how they were not constrained or prescribed by a priori theoretical/conceptual frameworks and their sensitizing concepts (Aldiabat & Le Navenec, 2018) that informed the initial research design.

In the interviews, I demonstrated relationship ethics by allowing participants to "assist in defining the rule" of how the interviews will unfold (Gonzalez, 2000, as cited in Tracy, 2010, p. 847). Even though several questions were generated in advance, I respected the participants' expertise for being intuitive to contribute relevant questions or critiques to improve existing questions (Carmichael & Cunningham, 2017). Critiquing of the questions was applicable to Teacher#2 and was addressed in a 30-minute member check prior to the semi-structured interview. Memo#52_Member Check with Teacher#2 captures this very well.

> Memo#52_Member Check with Teacher#2
> DATE: August 19, 2022
> THEME: Member Check with Teacher#2
>
> This morning, I completed a member check with Teacher#2 via phone. After reviewing the questions I shared with her on 8-14-22, she wanted to rephrase and correct some of the excerpts that will be used in the interview this evening, in addition to asking clarifying questions regarding the initial set of interview questions. From her tone, I gathered that she was uncomfortable with the excerpts addressing the easiness of the task. I reassured her that the aim of my research is to help teachers …. I explained that the questions were structurally written and arranged to go from general to specific in clarifying the teacher's response.

Ethical Considerations

Besides relationship ethics, other ethical considerations that are integrated into the research design include internal review board (IRB) training and approval, informed consent, privacy, and confidentiality. In keeping with Long Island University's research protocol for working with human subjects, I completed the online IRB training program—Collaborative Institutional Training Initiative (CITI)—in the Summer of 2021. In addition, I sought the approval of the university's IRB committee before recruiting participants in January 2022. Of equal importance, I sought and received the approval of the participating district's IRB committee before recruiting their science teachers in June 2022.

Adhering to the federal regulation addressed in *Subpart A of 45 CFR Part 46: Basic HHS Policy for Protection of Human Subjects* (U.S. Department of Health and Human Services (HHS) et al., 2018), prior to the data collection, I obtained consent from the science teachers. Specifically, I provided the LIU informed consent form to the participants via email. In the consent form, the benefits of participating in the study were also addressed as well as assurances of no negative consequences from refusing to participate or withdraw from the study.

To maintain privacy and confidentiality as required by federal regulations, I generated a pseudonym (Corti et al., 2020; Jones et al., 2014, 2021; Saldaña & Omasta, 2018) for participants, specifically, an ID variable (Berenson, 2018) specifically Teacher#1, #2, #3, #4, and #5 which I used throughout the data collection, storage, analysis, and reporting processes. As a part of the data management protocol, the use of aggregate data (Corti et al., 2020; Saldaña & Omasta, 2018) over individual data was applied during analysis (i.e., in the generation of found poetry) and reporting (i.e., in the generation of theory). Moreover, the research data was password protected (Corti et al., 2020; Jones et al., 2014, 2021; Saldaña & Omasta, 2018) on my personal computer and only the de-identified data was shared with members of the dissertation committee, and peer reviewers to gain additional professional perspective as a validity-enhancing strategy (Creswell & Miller, 2000).

Limitations

By design, research anchored in the constructivist paradigm is prone to researcher subjectivity because the researcher is serving as the instrument (Aldiabat & Le Navenec, 2018; Jones et al., 2014; Mason, 2018; Merriam, 2007; Saldaña & Omasta, 2018) of data collection and analysis. In essence, would another researcher interpret the findings of my study to generate a similar theory? Thus, to mitigate this inherent issue related to the researcher's theoretical and paradigmatic orientation, I integrated several strategies including member checks/reflections of data and advisor/peer reviews of coding themes which aid in the reduction of validity threats (Aldiabat & Le Navenec, 2018; Creswell & Miller, 2000; Tracy, 2010).

CHAPTER 4: FINDINGS

In this chapter, the findings of the study are revealed. To execute this task in a manner that is transparent and does not diminish/sacrifice the descriptive validity—that is the methodological decisions[65] that I have made as a part of the codebook development/management protocols (Cohen et al., 2018; Corti et al., 2020; Ravitch & Carl, 2019; Tracy, 2010)—I have commenced the chapter with a section on methodological decisions during codebook development and management. Since no research is immune to "challenges and unexpected twists and turns" (Tracy, 2010, p. 842), in the second section of this chapter, I share my journey in navigating the research ecosystem in my dual roles as a practitioner-researcher. This organizational framework offers a logical segue into the third section that leverages the codebook and the derived/synthesized assertions to answer the first of two research questions (i.e., What are the thought processes used by secondary science teachers in interpreting students' scientific models that are comprised of drawing activities?), thus revealing the science teachers' thoughts about how they interpret students' scientific models that are comprised of drawings. Laying the groundwork established with the first research question, the fourth section addresses the second question (i.e., In what way does culture play a role in secondary science teachers' thought processes when interpreting students' scientific models that are comprised of drawing activities?) to reveal the role that culture plays in science teachers' thought processes. This section creatively expresses and summarizes the CGT using found poetry and a diagrammatic display/axial coding paradigm (Creswell & Poth, 2018; Saldaña & Omasta, 2018). The final section summarizes the findings.

[65] Being transparent about these methodological decisions reduces the need for external validation (Cohen, et al., 2018).

Methodological Decisions During Codebook Development and Management

To demonstrate sincerity, qualitative researchers need to be transparent about the methodological decisions that shape their codebook development and management (Tracy, 2010). In keeping with the spirit of sincerity, I disclose seven relevant methodological decisions that have shaped the development of the codebook (see Table 2). These decisions address the transcription protocol, the use of sensitizing concepts as a priori data, the role of the pilot study, my coding approach, integrating the literature, tentative theorizing, and data reduction protocol.

Moving forward, in the codebook and throughout the remaining sections of the dissertation, I have embraced the coding style of Saldaña (2016) and Saldaña and Omasta (2018) whereby, in vivo codes are capitalized, subcategories are bolded and italicized, categories are bolded, and themes are bolded and capitalized. See Figure 8. With respect to the in vivo codes being capitalized, exceptions were made for chemistry symbols where applicable in the codebook. For example, sodium atom was written as “Na” instead of “NA” to preserve the notation used by the science teacher and to prevent confusion for members of the chemistry community. Another exception included captilazing and bolding the the in vivo codes to emphasize portions of the code. See dialogue from Example 3: The Reflective Reseacher Changing Perspective on the Journey.

Table 2

Codebook of Science Teachers’ Thought Processes

DIRECTIONS OR RULES	*Attribute:* This thought occurs when science teachers expect students to abide by given directions or rules.
Deviating From Directions or Rules	*Attribute(s):* When science teachers observe that students are not following explicit or implicit directions or rules. *Indicators:* Coded when the science teachers said: (1) “THAT'S

<table>
<tr><td></td><td>NOT WHAT IT SAYS TO DO;” (2) “I HAVE SEEN SOME OF YOU CHANGING THE FORMULA, BUT YOU CANNOT CHANGE THE FORMULA IN ORDER TO BALANCE THE EQUATION;” (3) “THEY'RE PUTTING THE ATTRACTION OF THE BONDING ON THE WRONG SIDE, LIKE POSITIVE TO POSITIVE;” and (4) “YOU'RE MISSING A STEP FOR STEP THREE.”

Diversity of the Category: It was observed in all teachers.

Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>2</td><td>49</td><td>4</td><td>9</td><td>8</td></tr>
</table></td></tr>
<tr><td>Following Directions or Rules</td><td>Attribute(s): This thought occurs when science teachers expect students to abide by given rules or sets of directions.</td></tr>
<tr><td>Following Explicit Rules</td><td>Attribute(s): This thought occurs when science teachers (a) use student-friendly language that simplifies rules, (b) share the exact directions/steps for students to follow, and (c) share what should not be done.

Indicators: Coded when the science teachers said: (1) “DO NOT CHANGE YOUR FORMULA TO BALANCE THE EQUATION;” (2) “YOU NEED TO MAKE SURE YOU INCLUDE THIS;” and (3) “I WANNA SEE 20 ARROWS.”

Diversity of the Category: It was observed in all teachers.

Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>10</td><td>30</td><td>24</td><td>46</td><td>8</td></tr>
</table></td></tr>
<tr><td>Following Implicit Rules</td><td>Attribute(s): This thought occurs when science teachers use vague/disciplinary cultural language that complicates students’ understanding of the rules which results in students asking for clarification multiple times.

Indicators: Coded when the science teachers said: (1) “YOU ARE NOT DOING THIS RIGHT.” (2) “HOW DO WE SEE NEWTON'S FIRST LAW IN THIS?” and (3) “WHAT ARE YOU CONFUSED ABOUT? YOU ARE MOVING THE COMPASS.”

Diversity of the Category: It was observed in all teachers.

Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>7</td><td>26</td><td>1</td><td>23</td><td>13</td></tr>
</table></td></tr>
</table>

<table>
<tr><td>Having Choices and Freedom</td><td>Attribute(s): This thought occurs when science teachers provide students with choices and freedom.

Indicators: Coded when science teachers said: (1) “THEY HAD THE FREEDOM TO GO ON AND ADD MORE RESISTERS, MORE LEDS;” (2) “SO AS LONG AS THEY KNOW THE CONCEPT …, AS LONG AS THEY HAVE THE UNDERSTANDING HOW IT WORKS…, THEY CAN MAKE IT AS CREATIVE AS POSSIBLE;” and (3) “ESPECIALLY WITH THAT PARTICULAR ACTIVITY, LIKE IT'S SO MANY ENDLESS POSSIBILITIES.”

Diversity of the Category: It was observed in all teachers.

Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>10</td><td>9</td><td>1</td><td>4</td><td>1</td></tr>
</table></td></tr>
<tr><td>FORMS OF COMMUNICATION</td><td>Attribute(s): This thought occurs when science teachers expect to see common signs/symbols, language, and logic.</td></tr>
<tr><td>Common Forms of Communication</td><td>Attribute: Communication elements such as language, logic, and symbols that are shared between students and science teachers, and between students and the assessor.</td></tr>
<tr><td>Communicating a Shared Disciplinary Language</td><td>Attribute(s): This thought occurs when science teachers expect to see students using a common disciplinary language such as (a) labels, (b) descriptions, (c) vocabulary, (d) process/cause-effect relationships, and (e) scientific principles.

Indicators: Coded when science teachers said: (1) “KNOW THE BASIC VOCABULARY;” (2) “YOU NEED TO LABEL IT;” (3) “IT IS PART OF THE LAW OF CONSERVATION OF MOMENTUM;” and (4) “ACTION AND REACTION.”

Diversity of the Category: It was observed in all teachers.

Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>11</td><td>53</td><td>10</td><td>26</td><td>59</td></tr>
</table></td></tr>
<tr><td>Communicating a Shared Disciplinary Logic</td><td>Attribute(s): This thought occurs when science teachers expect to see a student using cross-disciplinary reasoning skills to demonstrate objectivity such as setting up a problem and piecing together relevant information in a creative way. When science teachers ask students to “explain” resulting in written scientific arguments beginning with “if” or “since” statements/premises.

Indicators: Coded when science teachers said or wrote: (1) “SINCE THE WEIGHT AND THE NORMAL FORCES</td></tr>
</table>

<table>
<tr>
<td></td>
<td>CANCEL OUT IN THE Y-DIRECTION, WE ONLY NEED TO WORRY ABOUT THE FORCES IN THE X-DIRECTION. THE NET FORCE IS THUS 50 – 30 = 20 N (+X-DIR);” (2) “IF THERE WAS ONLY ONE ROCKET-POWERED AUTOMOBILE ON THE ROAD, IT WOULD WORK FINE. HOWEVER, IMAGINE RUSH HOUR TRAFFIC LOADED WITH ROCKET CARS. EACH WOULD BLOW EXHAUST GAS AT THE VEHICLES TO THE REAR;” (3) “I INTERPRET LOGIC AS THOSE ASPECTS OF AN APPROACH TO A PROBLEM THAT [IS] CROSS-DISCIPLINARY;” (4) “I KNOW THAT LAW HAS THE SAME KIND OF REASONING SKILLS;” (5) “I'M TEACHING THEM A WAY OF OBJECTIVITY;” and (6) “SINCE MAGNESIUM IS BY ITSELF, IT'S 0 OXIDATION STATE. SULFUR BY ITSELF IT'S 0. NOW IN THE COMPOUND MAGNESIUM IS A METAL. SO IT BECOMES POSITIVE 2, AND HOW 0 BECAME POSITIVE 2, BECAUSE MAGNESIUM GOT RID OF 2 ELECTRONS.”

Diversity of the Category: It was observed in Teachers 4 and 5 but not observed in Teachers 1, 2, and 3.

Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>0</td><td>47</td><td>0</td><td>30</td><td>11</td></tr>
</table>
</td>
</tr>
<tr>
<td>Communicating Shared Disciplinary Symbols</td>
<td>Attribute(s): This thought occurs when science teachers expect to see students using conventional signs/symbols of the discipline in the (a) location, (b) proximity, (c) orientation, (e) direction, and (f) size that is relevant to the context.

Indicators: Coded when science teachers said or wrote: (1) “WHEN IT'S A DIATOMIC MOLECULE, YOU NEED TO SHOW ME THEM CONNECTED TOGETHER;” (2) “I WANTED THE ARROWS IN THE RIGHT DIRECTION;” (3) “AS LONG AS IT'S VISUALLY LARGER, THAT'S ENOUGH TO REPRESENT;” (4) “CLEARLY STUDENT HAS [AN] IDEA ABOUT THE SIZES OF THESE ATOMS, ALSO BECAUSE NITROGEN AND OXYGEN ARE VERY CLOSE TO EACH OTHER, SO THEIR SIZE IS ALMOST SAME;” (5)“THE DIRECTION OF ELECTRONS IS RIGHT, TOO;” and (6) “LIST REACTANTS ON THE LEFT SIDE OF THE REACTION ARROW AND PRODUCTS ON THE RIGHT SIDE.”

Diversity of the Category: It was observed in all teachers.</td>
</tr>
</table>

<table>
<tr><td></td><td>Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>22</td><td>65</td><td>32</td><td>77</td><td>49</td></tr>
</table></td></tr>
<tr><td>Uncommon Forms of Communication</td><td>Attribute: Communication elements such as language, logic, and symbols that are not shared between students and science teachers, between students and the assessor.</td></tr>
<tr><td>Missing or Confusing the Disciplinary Language</td><td>Attribute(s): This thought occurs when science teachers do not see the common language such as students missing labels or descriptions of processes, or there is evidence that the students are confusing the language.

Indicators: Coded when science teachers said: (1) “WITHOUT LABELING IT, IT IS DIFFICULT TO FIGURE OUT WHAT EXACTLY THEY WERE TRYING TO COMMUNICATE;” (2) “DID NOT WRITE THE SENTENCE, BECAUSE HERE HE'S CLEARLY SHOWING IRON UNDERGOES OXIDATION;” (3) “THEY CALL SOMETHING THAT'S A PUSHING FORCE,…CALL IT TENSION;” and (4) “IF THEY DID NOT LABEL THIS FORCE, THEY WERE REALLY MISSING HOW THIS THING WAS MOVING.”

Diversity of the Category: It was observed in all teachers.

Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>1</td><td>9</td><td>1</td><td>6</td><td>7</td></tr>
</table></td></tr>
<tr><td>Missing or Confusing the Disciplinary Logic</td><td>Attribute(s): This thought occurs when science teachers recognize that parts of students’ reasoning are missing. When students’ ideas are strung together in a way that seizes the 2-way communication. This results in the interpreter/reader having difficulty interpreting and understanding the reasoning/message/argument. The concept used by the author/explainer has a different value/meaning depending on the position in which they are used in the scientific argument.

Indicators: Coded when science teachers said: (1) “IF THERE'S PARTS MISSING LIKE THEIR LOGIC.” (2) “THEY ARE ABLE TO TELL IF THEIR FORCES ARE EQUAL, LESS THAN OR GREATER TO, BUT THEN THEY CAN'T EXPLAIN WHY;” and (3) “STUDENT IS SAYING THAT IRON IONS ARE INCREASING BUT DOESN'T TELL ME WHY.”

Diversity of the Category: It was observed in Teachers 2, 4, and 5 but not observed in Teachers 1 and 3.</td></tr>
</table>

<table>
<tr><td></td><td>Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>0</td><td>16</td><td>0</td><td>8</td><td>3</td></tr>
</table></td></tr>
<tr><td>Missing or Confusing the Disciplinary Symbols</td><td>Attribute(s): This thought occurs when science teachers (a) do not see the conventional symbols, (b) there is evidence that students are confusing the symbols, their location, and size, or (c) there is evidence of confusing the context in which the conventional symbols are used.

Indicators: Coded when science teachers said: (1) “SOME OF YOU ARE SAYING TO BALANCE THE EQUATION, Na + Cl_2, JUST WRITE $NaCl_2$ DONE. YOU CANNOT DO THAT. THERE IS NO SUCH THING IN THE UNIVERSE AS $NaCl_2$;” (2) “I SEE A CLUSTER OF ATOMS. I DON'T SEE A COMPOUND THERE.” (3) “USING SIGMA TO DESCRIBE A COEFFICIENT OF FRICTION INSTEAD OF MU, THOSE THINGS I HAVE TO CORRECT;” (4) “SHE DIDN'T ADDRESS ANY OF THE OF THE FORCES OF THE BALLOON, WHICH I FEEL LIKE SHE MISSED;” and (5) “HAVE THE SIZE OF THE ARROW BE COMPARABLE TO THE … AMOUNT OF FORCE, AND I FELT LIKE THAT GOT LOST A LITTLE BIT TOO WITH THIS GROUP.”

Diversity of the Category: It was observed in all teachers.

Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>1</td><td>43</td><td>2</td><td>7</td><td>12</td></tr>
</table></td></tr>
<tr><td>CREATIONS</td><td>Attribute: This thought occurs when science teachers observe students’ drawings.</td></tr>
<tr><td>Deviating From Identical or Similar Creations</td><td>Attribute(s): This thought occurs when science teachers see drawings of students that (1) do not mimic the text, teacher, self, or peer (2) are simple and preliminary, and (3) are reconceptualizations.

Indicators: Coded when science teachers said: (1) “SOMETIMES THE DIAGRAMS ARE NOT CLEAR;” (2) “NO IS NOT NITRATE. NO ITSELF IS A COMPOUND, NITRIC OXIDE. THAT IS NOT NITRATE ION. SO THIS IS NOT CORRECT;” (3) “THEY'RE PUTTING THE ATTRACTION OF THE BONDING ON THE WRONG SIDE, LIKE POSITIVE TO POSITIVE FROM ONE;” and (4) “I WAS INTERPRETING HER MODEL...AND I WAS SEEING SOME MISSING INFORMATION TO MAKE IT COMPLETE.”

Diversity of the Category: It was observed in all teachers.</td></tr>
</table>

Code Frequency:

Teacher	1	2	3	4	5
Frequency	5	25	2	9	6

Having an Identical or Similar Creation With Others or the Self.

Attribute: This thought occurs when science teachers see drawings of students mimicking a peer, self-created model, teacher, textbook, or reference.

Having an Identical or Similar Creation with a Peer

Attribute(s): This thought occurs when science teachers see drawings of students mimicking a peer.

Indicators: Coded when science teachers said: (1) “LOOK AT HER FULL EQUATION TO FIGURE IT OUT;” (2) “STUDENT#1, CAN I BORROW YOUR PAPER TO EXPLAIN SOMETHING;” and (3) “THIS HAS STUDENT#2. YOU SEE HER WATER MOLECULES…WITH THE DASH LINE, SHE'S SHOWING THE HYDROGEN BONDING.”

Diversity of the Category: It was observed in Teachers 1, 2, 3, and 4 but not observed in Teacher 5.

Code Frequency:

Teacher	1	2	3	4	5
Frequency	1	5	4	1	0

Having an Identical or Similar Creation With a Self-Created Model

Attribute(s): This thought occurs when science teachers see drawings of students mimicking an associated model created by the student.

Indicators: Coded when science teachers said: (1) “THEY WERE ABLE TO DRAW IT AND IT MATCHED WHAT THEY DID;” (2) “I AM GOING TO ASK YOU TO DRAW THESE MODELS TO BALANCE THE EQUATION;” and (3) “SO THE MODEL DID MATCH WHAT HE ACTUALLY PUT TOGETHER ON HIS BREADBOARD”

Diversity of the Category: It was observed in Teachers 1, 2, and 4 but not observed in Teachers 3 and 5.

Code Frequency:

Teacher	1	2	3	4	5
Frequency	2	5	0	1	0

Having an Identical or Similar Creation With the Teacher

Attribute(s): This thought occurs when science teachers see drawings of students mimicking those drawn by the teacher.

Indicators: Coded when science teachers said: (1) “I JUST WANTED TO SEE LIKE THE SAME EXAMPLE;” (2)

<table>
<tr><td></td><td>“THOSE OF YOU WHO ARE NOT ABLE TO DO IT, AT LEAST COPY MY WORK;” and (3) “I WAS LOOKING FOR 5 THINGS IN THIS PICTURE.”

Diversity of the Category: It was observed in all teachers.

Code Frequency:
Teacher: 1 | 2 | 3 | 4 | 5
Frequency: 5 | 25 | 5 | 3 | 7</td></tr>
<tr><td>Having an Identical or Similar Creation With the Textbook or Reference</td><td>Attribute(s): This thought occurs when science teachers see drawings of students mimicking the textbook or a reference.

Indicators: Coded when science teachers said: (1) “THEY HAD TEMPLATES;” (2) “USUALLY ON THE REGENTS, SO THE KEY FROM THE STATE SAYS THEY SHOULD PUT THE ARROW ON THE WIRE THAT ELECTRONS ARE MOVING;” and (3) “THERE'S A LOT OF ANIMATION.”

Diversity of the Category: It was observed in Teachers 1, 2, 3, and 4 but not observed in Teacher 5

Code Frequency:
Teacher: 1 | 2 | 3 | 4 | 5
Frequency: 4 | 6 | 2 | 2 | 0</td></tr>
<tr><td>Having Multiple or Different Creations</td><td>Attribute(s): This thought occurs when science teachers accept multiple or different representations of a drawing activity.

Indicators: Coded when science teachers said or wrote: (1) “3 DIFFERENT WAYS OF DOING THINGS;” (2) “THE ONLY THING THAT IS IN OUR HANDS IS PUTTING THE NUMBER IN THE FRONT WHICH TELLS US HOW MANY OF THE PRODUCT IS PRODUCED;” (3) “THEY SAY UP OR NORTH OR Y, THINGS LIKE THAT AND NEGATIVE Y UP, UP IS POSITIVE AND DOWN AS NEGATIVE I'M LIKE THAT'S NOT A LAW, THAT'S JUST CONVENTION, AND THERE ARE CERTAIN THINGS THAT YOU DO CONVENTIONALLY. BUT, IF YOU WANT TO FLIP THE AXES AROUND, SO THE NEGATIVE GOES UP, BECAUSE IT'S EASIER FOR YOU TO DESCRIBE OR COMMUNICATE WHAT YOU'RE TRYING TO SAY THAT'S PERFECTLY ACCEPTABLE, AS LONG, AS YOUR READER UNDERSTANDS THAT YOU FLIPPED EVERYTHING AROUND JUST TO MAKE YOUR EXPLANATION MORE YOU KNOW, IT'S PERFECTLY OKAY;” and (4) “MANY DESIGNS ARE POSSIBLE.”</td></tr>
</table>

<table>
<tr><td></td><td>Diversity of the Category: It was observed in all teachers.

Code Frequency:<table><tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>Frequency</td><td>8</td><td>18</td><td>4</td><td>16</td><td>4</td></tr></table></td></tr>
<tr><td>INTERPRETATION OR UNDERSTANDING</td><td>Attribute: This thought occurs when science teachers see students having interpretations/understandings similar/identical to the teacher, text, or peer.</td></tr>
<tr><td>Confusing or Simplifying the Interpretation or Understanding</td><td>Attribute(s): This thought occurs when the science teachers observe students’ interpretations/understandings (a) contradicting the teacher's interpretations/conventional rules/norms of the discipline, (b) showing a simplistic preliminary understanding, and (c) lacking an explanation or elaborate explanation when one is warranted or lacking clarity or cohesiveness.

Indicators: Coded when science teachers said: (1) “YOU CANNOT ADD ONE. HYDROGEN EXISTS AS A DIATOMIC MOLECULE;” (2) “IT IS VERY GENERAL. IT'S NOT REALLY A SCIENTIFIC STATEMENT;” (3) “IF THEY DID NOT DRAW THE ARROW RIGHT HERE, WHERE THE AIR WAS COMING OUT OF THE STRAW, THAT'S WAS A PRETTY DEAD GIVEAWAY THAT THEY WERE MISSING THE POINT;” (4) “THE IDEAS ARE NOT QUITE COHESIVE;” and (5) “THEIR EXPLANATION IS INCOMPLETE.”

Diversity of the Category: It was observed in Teachers 2, 3, 4, and 5 but not observed in Teacher 1.

Code Frequency:<table><tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr><tr><td>Frequency</td><td>0</td><td>18</td><td>2</td><td>16</td><td>4</td></tr></table></td></tr>
<tr><td>Finding a Common Interpretation or Understanding With Others or the Self</td><td>Attribute: This thought occurs when science teachers observe that students’ interpretations/understandings are similar or identical to a peer, a self-created model, the teacher, a textbook, a reference, or a rubric.</td></tr>
<tr><td>Finding a Common Interpretation or Understanding With a Peer</td><td>Attribute(s): This thought occurs when science teachers observe that students’ interpretations/understandings are similar or identical to a peer.

Indicators: Coded when science teachers said: (1) ‘‘FOLLOWING STUDENT#1’S INTERPRETATION;” (2) “AT LEAST LEARN FROM OTHER STUDENTS' WORK; ” and (3) “I LOOK FOR AN ABILITY TO TURN AROUND AND EXPLAIN, NOT TO ME, … BUT TO THEIR FELLOW STUDENTS.”</td></tr>
</table>

Diversity of the Category: It was observed in Teachers 1, 2, 3, and 4 but not observed in Teacher 5.

Code Frequency:

Teacher	1	2	3	4	5
Frequency	2	2	4	5	0

Finding a Common Interpretation or Understanding With a Self-Created Model

Attribute(s): This thought occurs when science teachers observe that students' interpretations/understandings are similar or identical to an associated model created by the student.

Indicators: Coded when science teachers said: (1) "THEY SHOULD BE ABLE TO INTERPRET THEIR UNDERSTANDING OF WHAT THEY PICKED UP DURING THE ACTIVITY;" and (2) "WHEN STUDENTS WERE BALANCING EQUATIONS AND BUILDING MODELS, SOME STUDENTS WERE ABLE TO FIGURE OUT THAT IF THE NUMBER OF ATOMS ON EITHER SIDE [IS] NOT EQUAL, THEN THEY NEED TO CHANGE THE NUMBER OF MOLECULES BEFORE THE ARROW MEANS THAT IN THE REACTANTS OR AFTER THE ARROW MEANS AMONG THE PRODUCTS; BUILDING THEIR PARTICLE MODELS, SOME OF THEM WERE ABLE TO ACTUALLY FIGURE OUT HOW MANY MOLECULES THEY NEED BECAUSE THE NUMBER OF ATOMS DID NOT ADD UP TO PROVE THE LAW OF CONSERVATION OF MASS."

Diversity of the Category: It was observed in Teachers 1 and 2 but not observed in Teachers 3, 4, and 5.

Code Frequency:

Teacher	1	2	3	4	5
Frequency	1	1	0	0	0

Finding a Common Interpretation or Understanding With the Teacher

Attribute(s): This thought occurs when science teachers observe that the students' interpretations/understandings are similar or identical to their teachers'.

Indicators: Coded when science teachers said: (1) "IF I COULD INTERPRET WHAT THEY DID;" (2) "IT HELPS US, OR THE PERSON GRADING THEIR WORK, SHOWS THAT THEY HAVE UNDERSTANDING;" and (3) "BUT, CAN YOU MAKE IT SENSE MAKES SENSE TO ME?"

Diversity of the Category: It was observed in *all* teachers.

Code Frequency:

	Teacher: 1 / 2 / 3 / 4 / 5 Frequency: 3 / 24 / 5 / 53 / 52
Finding a Common Interpretation or Understanding With the Textbook, Reference, or Rubric	*Attribute(s):* This thought occurs when science teachers observe that the student's interpretation/understanding is similar or identical to the text, reference, or rubric/assessment criteria. *Indicators:* Coded when science teachers said: (1) "YOU WILL LOOK FOR THE FORMULA IN THE REFERENCE TABLE;" (2) "MINE IS… BASICALLY A VERY DETAILED RUBRIC THAT COMES DIRECTLY FROM ... THE INTERNATIONAL BACCALAUREATE PROGRAM;" (3) "YOU HAVE TO CONSIDER THE AUDIENCE THEY ARE TESTING FOR;" (4) "WE WATCHED A VIDEO;" and (5) "I HAD DIAGRAMS FOR THEM TO FOLLOW, AND THEN THEY HAD TO REINTERPRET BACK." *Diversity of the Category:* It was observed in *all* teachers. *Code Frequency:* Teacher: 1 / 2 / 3 / 4 / 5 Frequency: 5 / 12 / 2 / 52 / 29
Having Multiple or Different Interpretations or Understandings	*Attribute(s):* This thought occurs when science teachers recognize and accept that students have multiple/different/alternative interpretations and understanding of a drawing activity. *Indicators:* Coded when science teachers said: (1) "IT'S LIKE YOU'RE PUTTING A NOVEL IN A CLASSROOM OF 30 STUDENTS AND THEN DISCUSSING IT AND GIVING 30 DIFFERENT INTERPRETATIONS. IT'S LIKE THAT; " and (2)" SHE HAD THE FLOOR AS A FORCE WHICH I THOUGHT WAS KIND OF INTERESTING CAUSE I'M LIKE, WOULD I CONSIDER THE FLOOR A FORCE? BUT, I GUESS YOU COULD. YOU COULD BECAUSE THE RACER IS ...PUSHING UP AGAINST IT, YOU KNOW WHAT I MEAN? SO THAT WAS SOMETHING THAT WAS A PIECE THAT I DIDN'T QUITE THINK ABOUT UNTIL SHE HAD BROUGHT IT UP." *Diversity of the Category:* It was observed in Teachers 4 and 5 but not observed in Teachers 1, 2, and 3. *Code Frequency:* Teacher: 1 / 2 / 3 / 4 / 5 Frequency: 0 / 0 / 0 / 6 / 6

<table>
<tr><td>PROBLEM-SOLVING HEURISTICS DURING STUDENTS' STRUGGLES</td><td>Attribute: This thought occurs when science teachers encounter students struggling during a drawing activity and offer strategies to foster students’ successful completion of the drawing activity.</td></tr>
<tr><td>Trying to Make Sense of Students' Struggles</td><td>Attribute(s): This thought occurs when science teachers encounter students struggling in the modeling process such as being unable to successfully complete the modeling task and displaying help-seeking cues.

Indicators: Coded when science teachers said: (1) “I WAS WALKING BY AND THEY WERE ABLE TO WRITE, LET'S SAY ALUMINUM AND THEN THEY WERE STUCK HERE HOW TO WRITE UP 2 NITRATES;” (2) “THEY ASK FOR HELP;” and (3) “SO I DEFINITELY SEE FIGHTING WITHIN THE GROUP. I WILL SEE, WELL, YOU GO ASK HER.”

Diversity of the Category: It was observed in all teachers.

Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>4</td><td>6</td><td>5</td><td>4</td><td>5</td></tr>
</table></td></tr>
<tr><td>Using Heuristics</td><td>Attribute: This thought occurs when science teachers try to make it easy for students during a challenging modeling process by using solutions that worked in the past.</td></tr>
<tr><td>Clarification Heuristic</td><td>Attribute(s): When the teacher encounters students' misconceptions/struggles during a drawing activity and provides further whole-class clarification of the rule via (a) repeating the rule, (b) reminding students of the rule, (c) providing examples with prior associated experience, (d) debating aspects of the rule, (e) asking students a question regarding the rule, or (f) offering a suggestion/ having their peers offering suggestions about the rule.

Exclusion Criteria: Data that consist of a series of guided questions as observed in the multiple-choice heuristics.

Indicators: Coded when science teachers said: (1) “IN THE REACTION CONTAINER, DO YOU THINK THERE IS ONLY ONE SODIUM? THERE ARE MILLIONS OF THEM;” (2) “I REMINDED THEM,...HOW DOES … EACH WATER MOLECULE, HOW DO THEY CONNECT TO EACH OTHER?;” (3) “BRINGING IT BACK TOGETHER AS A WHOLE CLASS IS ALWAYS A WAY I CLEAR UP ANY MISCONCEPTIONS;” and (4) “SOMETIMES I MIGHT STOP AND DO A WHOLE DAY WHERE THEY ARE JUST DEBATING, WHY SOMETHING IS MORE DESCRIPTIVE OF WHAT'S TRYING TO BE EXPRESSED THEN</td></tr>
</table>

<table>
<tr><td></td><td>SOMETHING ELSE?”

Diversity of the Category: It was observed in Teachers 2, 3, 4, and 5 but not observed in Teacher 1.

Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>0</td><td>5</td><td>7</td><td>12</td><td>7</td></tr>
</table></td></tr>
<tr><td>Collaborative Group Heuristic</td><td>Attribute(s): This thought occurs when science teachers recognize students’ struggles and pair them up by ability, or when science teachers encourage students to discuss with their neighbors when they are stuck.

Indicators: Coded when science teachers said: (1) “THEY PAIR UP AND THEY HELP EACH OTHER;” (2) “IF YOU GET STUCK, YOU CAN DISCUSS WITH YOUR NEIGHBOR;” and (3) “WELL YOU AND YOUR PARTNER HERE HAVE TO START FIGURING OUT HOW TO MAKE SOME ADJUSTMENTS.

Diversity of the Category: It was observed in Teachers 3, 4, and 5 but not observed in Teachers 1 and 2.

Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>0</td><td>0</td><td>4</td><td>3</td><td>4</td></tr>
</table></td></tr>
<tr><td>Letter or Syllable Suggestion Heuristic</td><td>Attribute(s): This thought occurs when science teachers encounter students' misconceptions/struggles during a drawing activity and provide students clues to generate the appropriate language by offering suggestions involving starting letters or syllables.

Indicators: Coded when science teachers said: (1) “IT BEGINS WITH THE LETTER(S) C CO;” and (2) “THE WORD I'M LOOKING FOR BEGINS WITH AN F.”

Diversity of the Category: It was observed in Teachers 3 and 5 but not observed in Teachers 1, 2, and 4.

Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>0</td><td>0</td><td>1</td><td>0</td><td>1</td></tr>
</table></td></tr>
<tr><td>Multiple Choice or Guided Questions Heuristic</td><td>Attribute(s): This thought occurs when science teachers encounter students' misconceptions/struggles during a drawing activity and provide students with guided questions in the form of multiple choice to aid students' understanding.</td></tr>
</table>

<table>
<tr>
<td></td>
<td>
Indicators: CODED WHEN SCIENCE TEACHERS SAID: (1) “WHAT IS THAT 2? 2 COPPER? 2 ZINC? CHARGE OF COPPER? WHAT DOES THAT 2 MEAN?” (2) “IS A HYDROGEN GOING TO HOOK UP WITH ANOTHER HYDROGEN OF ANOTHER WATER MOLECULE? OR IS THE HYDROGEN GOING TO HOOK UP WITH AN OXYGEN OF ANOTHER WATER MOLECULE? WHERE IS HYDROGEN GONNA BOND WITH?” and (3) “WHY DO WE SEE THE CAR MOVE OR ACCELERATE AT CONSTANT VELOCITY AND NOT THE EARTH? IS IT DIFFERENT SIZES? DIFFERENT MASSES?”
Diversity of the Category: It was observed in Teachers 2, 3, 4, and 5 but not observed in Teacher 1.
Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>0</td><td>13</td><td>3</td><td>1</td><td>3</td></tr>
</table>
</td>
</tr>
<tr>
<td>Practice Drill Heuristic</td>
<td>
Attribute(s): This thought occurs when science teachers encounter students' misconceptions/struggles during a drawing activity and provide students with additional practice questions or tasks such as station activities.
Indicators: Coded when science teachers said: (1) “LET'S TRY ANOTHER ONE. IN YOUR BOOK ON PAGE 15, QUESTION 104, THE REACTION IS BETWEEN LITHIUM AND NITROGEN;” and (2) “YOU WILL START AT A LAB STATION AND THEN MOVE FROM STATION TO STATION UNTIL YOU HAVE COMPLETED ALL 8 ACTIVITIES.”
Diversity of the Category: It was observed in Teachers 2 and 4 but not observed in Teachers 1, 3, and 5.
Code Frequency:
<table>
<tr><td>Teacher</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Frequency</td><td>0</td><td>1</td><td>0</td><td>23</td><td>0</td></tr>
</table>
</td>
</tr>
<tr>
<td>Recognizing Aesthetic Appeal Heuristic</td>
<td>
Attribute(s): This thought occurs when science teachers compliment the aesthetics of the drawing offering praises about the drawing being pretty or beautiful to provide feedback to boost students’ confidence.
Indicator (s): Coded when science teachers said: (1) “THEY LOOK PRETTY;” (2) “THAT'S A LOVELY HORSE;” and (3) “THAT'S LOOKING NICE.”
</td>
</tr>
</table>

	Diversity of the Category: It was observed in Teachers 3, 4, and 5 but not observed in Teachers 1 and 2. *Code Frequency:* Teacher: 1, 2, 3, 4, 5 Frequency: 0, 0, 10, 2, 5
Resembling or Analogic Heuristic	*Attribute(s):* This thought occurs when science teachers encounter students' misconceptions/struggles during a drawing activity and point out/associate culturally familiar symbols that resemble or have features in common with the science target to facilitate students' understanding. *Indicators*: Coded when science teachers said or wrote: (1) "GIVE IT THE SHAPE OF MICKEY MOUSE;" (2) "ELECTRICITY IS LIKE WATER FLOWING THROUGH A HOSE;" and (3) "THE UNIVERSE IS LIKE A SHARK THAT STOPS MOVING, EVERYTHING DIES." *Diversity of the Category:* It was observed in Teachers 1, 3, and 4 but not observed in Teachers 2 and 5. *Code Frequency:* Teacher: 1, 2, 3, 4, 5 Frequency: 1, 0, 3, 1, 0
Show and Tell Heuristics	*Attribute(s):* This thought occurs when science teachers provide oral directions, break down the drawing task, model the task for students, and ask them to explain so they can take ownership. *Indicators*: Coded when science teachers said: (1) "MODELING IT FOR THEM;" (2)" IT'S ALMOST GUIDING THEM;" (3) "IT'S REALLY MORE OF ME LETTING THEM TELL ME WHERE THEY ARE AND HOW TO GUIDE THEM FROM THERE IN A WAY THAT THEY'RE TAKING OWNERSHIP OF THINGS;" and (4) "SOMETIMES I MIGHT GIVE A DIRECT RESPONSE TO THAT. I MAY SAY, WELL, ACTUALLY, YOU NEED TO MAKE SURE YOU INCLUDE THIS. LET'S LOOK AT HOW I MIGHT DO IT! HOW MIGHT YOU BE ABLE TO EXPLAIN THOSE IDEAS IN YOUR OWN WAY, IN A WAY THAT MAKES SENSE TO YOU?" *Diversity of the Category:* It was observed in Teachers 3 and 4 but, not observed in Teachers 1, 2, and 5. *Code Frequency:* Teacher: 1, 2, 3, 4, 5

	Frequency | 0 | 0 | 2 | 2 | 0
Starting from Scratch or Redesign Heuristic	*Attribute(s):* This thought occurs when science teachers encounter students' misconceptions/struggles during a drawing activity and asks students to repeat the modeling exercise or redesign the model. *Indicators*: Coded when science teachers said: (1) "IT'S ALWAYS EASIER TO START FROM SCRATCH;" (2) "IF THEY DO IT WRONG, THEN YOU KNOW THEY CAN REDO IT AGAIN;" and (3) "SO YOU ARE GONNA REDESIGN IT AFTER YOU TRY IT." *Diversity of the Category:* It was observed in Teachers 1, 3, and 5 but, not observed in Teachers 2 and 4. *Code Frequency:* Teacher | 1 | 2 | 3 | 4 | 5 Frequency | 6 | 0 | 3 | 0 | 1

Transcription Protocol

In developing the codebook (see Table 2: Codebook of Science Teachers' Thought Processes), I used low inference descriptors (Seale, 1999a, 1999b) in the form of intelligent verbatim quotations (Kawahara, 2007). That is, redundant words[66] (i.e., "the the") and disfluencies (i.e., "uh") (Kawahara, 2007) were eliminated to reflect a "more formal style of writing" (Brinkmann & Kvale, 2018, p. 109). Since the aim of the project was to reveal emergent themes rather than to produce a conversational analysis (Corti et al., 2020), the use of naturalized transcripts (Bucholtz, 2000; Nascimento & Steinbruch, 2019)—one that resembled written language—was a practical option. Despite the above modifications, the intelligent verbatim quotations still allowed me to stay close to the science teachers' thoughts as reflected by their words/voices in the codebook (Charmaz, 2000, as cited in Jones et al., 2014).

[66] Redundant words were consistently replaced with eclipses.

Use of Sensitizing Concepts as A Priori Data

> There is a difference between an open mind and [an] empty head. To analy[z]e data, we need to use accumulated knowledge, not dispense with it. The issue is not whether to use existing knowledge, but how. Our problem is to find a focus, without committing ourselves prematurely to a particular perspective and so foreclosing options for our analysis. (Dey, 1993, pp. 65-66)

Embracing the methodological wisdom of Dey (1993), I borrowed the concepts “signs and symbols” from two of the three theoretical frameworks—VST and CST—that I leveraged to gain an understanding of the central phenomena—scientific models that are comprised of drawings. Treating the composite—signs/symbols—as sensitizing concepts (Aldiabat & Le Navenec, 2018; Rossman & Rallis, 2017) allowed me as a novice researcher an initial direction to look in when working with the science teachers.

Pilot Study

In the Fall of 2020, I completed a pilot study examining a secondary school science teacher’s thought processes when he interpret scientific models comprised of drawings. In the pilot, using inductive coding, the category **Language** was revealed. Based on a sample of one participant, the pilot study sparked my interest in deeply exploring the literature and developing a more comprehensive understanding of the attributes of culture. See section: My Approach to Culture. This emanated from the participant’s confusion by the term “*culture”* when he was asked to speak about the role of cultural norms in his model-based instruction classroom. Recognizing the limitation of the definition that I had brought to bear to support an elaborate response from the participant, I continued my literature search in an attempt to expand my understanding. This led to improving the data collection questions in the current study.

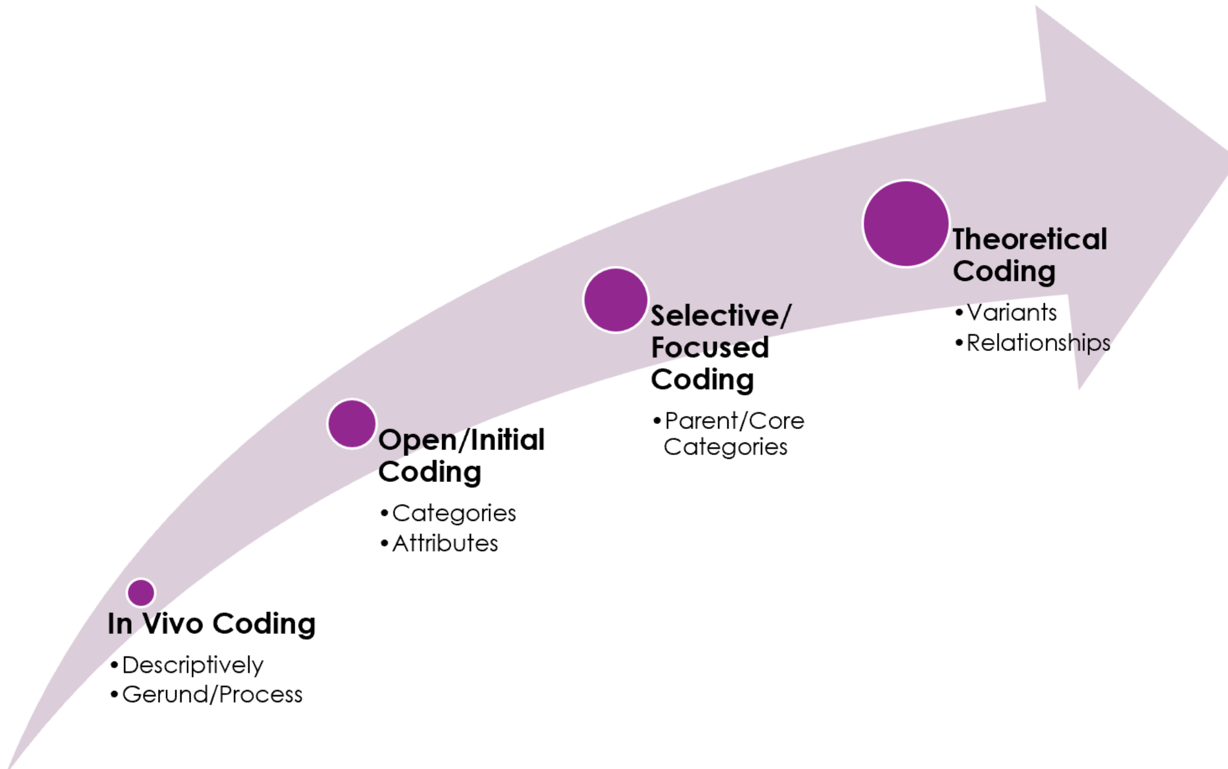
Consequently, in my dissertation, I have leveraged the category of **Language** deductively to aid in the initial coding of the data sets, since these are stages in the process of grounded theory methodology, inductive analysis to deductive analysis (Timmermans & Tavory, 2022).

My Approach to Coding

In the project, using NVivo, the intelligent verbatim transcripts (Kawahara, 2007) from the data collection methods were analyzed line by line using in vivo coding first descriptively (Carmichael & Cunningham, 2017; Leavy, 2017) and then with gerunds (Carmichael & Cunningham, 2017; Charmaz, 2020; Kenny & Fourie, 2015) or process coding (Carmichael & Cunningham, 2017; Kenny & Fourie, 2015; Saldaña, 2016; Saldaña & Omasta, 2018) to maximize the yield of rich data (Carmichael & Cunningham, 2017). These open/initial coding techniques allowed me to identify the emerging categories and their attributes (Urquhart, 2022). Next, using constant comparison, selective/focused coding (Timmermans & Tavory, 2022; Urquhart, 2022) was applied to cluster emerging categories into parent/core categories, and theoretical coding was leveraged to identify their variants and their relationships (Spradley, 1979, as cited in Roulston, 2010; Saldaña, 2016; Simmons, 2022; Urquhart, 2022). See Figure 10.

Figure 10

Coding Techniques Used to Create the Codebook



Gaining inspiration from several qualitative researchers (Boyatzis, 1998; Creswell & Creswell Báez, 2021; Saldaña, 2013, 2016), the final version of the codebook was re/organized in the dissertation to reflect the category label, attributes, indicators, and diversity (presence/absence in the science teachers) of the categories, exclusion criteria (where applicable), and code frequency. In some instances, "minor editorial changes in [the] wording" (Boyatzis, 1998, p. 108) and sequencing[67] were made without changing the essence of the attributes. Specifically, I revised all attributes to reflect that the science teacher is the agent since

[67] In this instance, I incorporated numbered and alphabetized lists for organization.

several of the attributes in the codebook unintentionally focused on the students. To do this, I used the sentence stem, "this thought occurs when science teachers…"

Integrating the Literature

Despite frequently using the direct voice of the participants or low inference descriptors (Seale, 1999a, 1999b), there were a few occasions when I adopted language from theoretical and empirical literature to gain a handle on how I was interpreting the data addressing the science teachers' cultural practice (Saldaña, 2013, 2016) in the changing research landscape. Using this coding approach allowed me to transcend the limitations of descriptive coding—that is, summarizing the science teachers' thoughts—and move towards an analytical coding approach of theorizing "what might be happening and what strategies [the science teachers] might be using" (Urquhart, 2022, p. 67). Importantly, this approach did not deviate from the bottom-up (Timmermans & Tavory, 2022; Urquhart, 2022) or inductive (Boyatzis, 1998; Carcary, 2020; Davoudi et al., 2016; Shank, 1993, November; Tavory & Timmermans, 2014; Timmermans & Tavory, 2022) coding approach that exemplifies the GT methodology since it was the language and behavior of the science teachers that guided the literature search and implementation. In other words, "the data …show[ed me] whether this literature [was] a relevant orientation point for the project" (Timmermans & Tavory, 2022, p. 28).

A relevant example of integrating the literature during data analysis as outlined above involved the category **Using Heuristics** which sequentially (Spradley, 1979, as cited in Roulston, 2010; Saldaña, 2016; Simmons, 2022; Urquhart, 2022) occurs with the category,

Trying to Make Sense of Students' Struggle.[68] See Table 2: Codebook of Science Teachers' Thought Processes. Initially recognized in Teacher#1 as: (1) "IT'S ALWAYS EASIER TO START FROM SCRATCH ," (2) "JUST PULL OUT EVERYTHING," (3) "PULL IT OFF IN SECONDS," (4) "REDO IT," (5) "LET'S REDRAW THE LINES," and (6) "YOU BETTER REMOVE IT AND START ALL OVER AGAIN." At first, I opted for using the language provided by Teacher#1 for the category nomenclature of **Starting from Scratch**, but ultimately I felt it was too specific. Being re/informed by Glaser's (1995) research, *Expert Knowledge and the Process of Thinking*, Schwartz and Cuadros' (2017) study, *The Effects of the Environment on Decision-Making*,[69] and personal communication with my advisor (Rhee, personal communication, July 6, 2022), I classified the veteran teacher as an expert (having over 20 years of science teaching experience) and the surprising/puzzling moment as an unfamiliar domain (Glaser, 1995) or stressful encounter in her environment (Schwartz & Cuadros, 2017), then I made a linguistic comparison (Martin, 2019) between the two studies which showed a common metric/variable, that is "HEURISTICS."

Tentative Theorizing

Timmermans and Tavory (2022) note that coding gives researchers marching orders. Being a science education practitioner, it seemed like a logical progression to generate several declarative statements (Saldaña & Omasta, 2018)─working hypotheses─from the data I was

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[68] In the first iteration of the codebook, the emerging category **Trying to Make Sense of Students' Struggles** was given the nomenclature **Trying to Make Sense of Students' Surprising/Puzzling Moments** but was revised to its current form with exposure to data from the subsequent participants.

[69]After dialoguing with my advisor regarding my methodological decision to treat Teacher#1 as an expert teacher and the effect of the research environment on decision making, a search query in Google Scholar using the phrase "how does research environment affect thinking and decision making" resulted in finding Schwartz and Cuadros' (2017) study.

observing. In an exploration of the literature, several scholars (Draucker et al., 2007; McNeill, 2004; Miles et al., 2020; Saldaña & Omasta, 2018; Urquhart, 2022) acknowledge that this practice is not a foreign approach in qualitative research. In light of this revelation, it gave me confidence/solace in this methodological decision. Consequently, after coding Teacher#1, I constructed six declarative statements/tentative explanations which I sought dis/confirming evidence (Cohen et al., 2018; Saldaña & Omasta, 2018) to substantiate or refute using the subsequent participants (Cohen et al., 2018; Miles et al., 2020; Saldaña & Omasta, 2018). See Table 3.

Table 3

Declarative Statements Generated from Teacher#1

Declarative Statement #1: Experienced science teachers use heuristic strategies when they encounter puzzling moments.	
Indicators	*Puzzling Moment:* Coded when Teacher#1 said: (1) “IT’S DIFFICULT TO FIGURE OUT” (2) “I WONDER WHY THIS ISN’T WORKING” *Heuristic:* Coded when Teacher#1 said: (1) “IT’S ALWAYS EASIER TO START FROM SCRATCH” (2) “JUST PULL OUT EVERYTHING” (3) “PULL IT OFF IN SECONDS” (4) “REDO IT” (5) “LET’S REDRAW THE LINES”
Declarative Statement #2: In interpreting students’ scientific models, science teachers look for a common interpretation, that is, an interpretation that is common with the teacher, peer, mediated textbook or reference, and student’s prior model.	
Indicators	*Teacher:* Coded when Teacher#1 said: (1) “IF I COULD INTERPRET WHAT THEY DID” (2) “I LIKE A LITTLE MORE LIKE ABLE TO FOLLOW IT IN DETAIL” Peer: Coded when Teacher#1 said: “[a]FOLLOWING STUDENT#1’S INTERPRETATION”

	Textbook or Reference: Coded when Teacher#1 said: (1) "I HAD DIAGRAMS FOR THEM TO FOLLOW, AND THEN THEY HAD TO REINTERPRET BACK" (2) "THEY ARE NOT FOLLOWING THE TECHNICAL ONE" (3) "BUT THEY COULD INTERPRET IT" *Student's Prior Model:* Coded when Teacher#1 said: "THEY SHOULD BE ABLE TO INTERPRET THEIR UNDERSTANDING OF WHAT THEY PICKED UP DURING THE ACTIVITY"
Declarative Statement #3: Science teachers are looking for students to demonstrate a common form of communication. Attributes of this code include learning the language, learning the symbol, missing the language, and missing the symbol.	
Indicators	*Learning the symbol:* Coded when Teacher#1 said: (1) "THEY SHOULD SHOW THEIR BATTERY SYMBOLS" (2) "THEY WERE INSTRUCTED TO USE RESISTORS. AND IF YOU HAD FILLED THAT IN, INSTEAD OF JUST THE POSITIVE AND THE NEGATIVE OF THE BATTERY TERMINUS" (3) "HAD TO HAVE THE REPRESENTATION, THE TWO BATTERIES" (4) "THE SYMBOLS THAT ARE SUPPOSED TO BE USED FOR THE LEDS HAVE TO BE IN THERE" (5) "THE RESISTOR SYMBOL HAS TO BE THERE" (6) "THEY MADE SURE SOME OF THE SYMBOLS THAT ARE USED" (7) "COLOR IS EVEN BETTER BECAUSE RIGHT AWAY IT STANDS OUT" *Missing the language*: Coded when Teacher#1 said: "WITHOUT LABELING IT, IT IS DIFFICULT TO FIGURE OUT WHAT EXACTLY THEY WERE TYRING TO COMMUNICATE" *Missing the symbol:* Coded when Teacher#1 said: "THEY DIDN'T COLOR IT THE WAY I DID COLOR"
Declarative Statement #4: In interpreting students' models, science teachers are looking for norm-conforming behaviors which address following directions or rules.	
Indicators	Coded when Teacher#1 said: (1) "I GAVE THE PAPER MODEL TO ANOTHER STUDENT AND ASKED HIM TO FOLLOW INSTRUCTIONS" (2) "THEY FOLLOWED THE EXACT DIRECTIONS" (3) "YOU ARE NOT DOING THIS RIGHT" (4) "DO STEP 1" (5) "DO STEP ONE BEFORE GOING AHEAD" (6) "THIS IS ABOUT FOLLOWING DIRECTIONS" (7) "FOLLOW THE DIRECTIONS" (stated 3x)

	(8) "FOLLOW THIS" (9) "GO STEP BY STEP" (10) " FOLLOW THE NUMBERS"
Declarative Statement #5: Science teachers are looking for students'examples to depict identical creations and recognize when students deviate from the identical creations.	
Indicators	*Identical creations:* Coded when Teacher#1 said: (1) "THEY WERE ABLE TO DRAW IT AND IT MATCHED WHAT THEY DID" (2) "SO THE MODEL DID MATCH WHAT HE ACTUALLY PUT TOGETHER ON HIS BREADBOARD" (3) "I GAVE THE PAPER MODEL TO ANOTHER STUDENT AND ASKED HIM TO FOLLOW INSTRUCTIONS" (4) "I HAD DIAGRAMS FOR THEM TO FOLLOW" (5) "THEY WERE SHOWN STANDARD CIRCUIT DIAGRAMS" (6) "SECOND ONE WAS I HAD PHYSICALLY AND THERE'S A PHOTOGRAPH OF IT" (7) "I JUST WANTED TO SEE LIKE THE SAME EXAMPLE" (8) "DUPLICATE THE SAME THING" (9) "DRAW IT LIKE THIS" *Deviating from identical:* Coded when Teacher#1 said: (1) "SOMETIMES THE DIAGRAMS ARE NOT CLEAR" (2) "THEY'RE NOT FOLLOWING THE ACTUAL TECHNICAL ONE" (3) "EVEN IF THE DETAILS WERE NOT AS A TEXTBOOK DRAWING, I WAS ACCEPTING THAT" (4) "STUDENTS' DRAWINGS, THEY DID NOT HAVE THE COLORS" (5) "THEY DIDN'T COLOR IT THE WAY I DID COLOR IT"
Declarative Statement #6: Science teachers reflect on the plurality of choices and freedom that students are given to construct their own models.	
	Coded when Teacher#1 said: (1) "STUDENTS WERE GIVEN THE FREEDOM" (2) "3 DIFFERENT WAYS OF DOING THINGS" (3) "RECONSTRUCT IT IN THEIR OWN WAY" (4) " FREEDOM TO GO ON" (5) "EVEN IF THE DETAILS WERE NOT AS A TEXTBOOK DRAWING, I WAS ACCEPTING THAT"

Note. [a]Identification variable used as a pseudonym for a student.

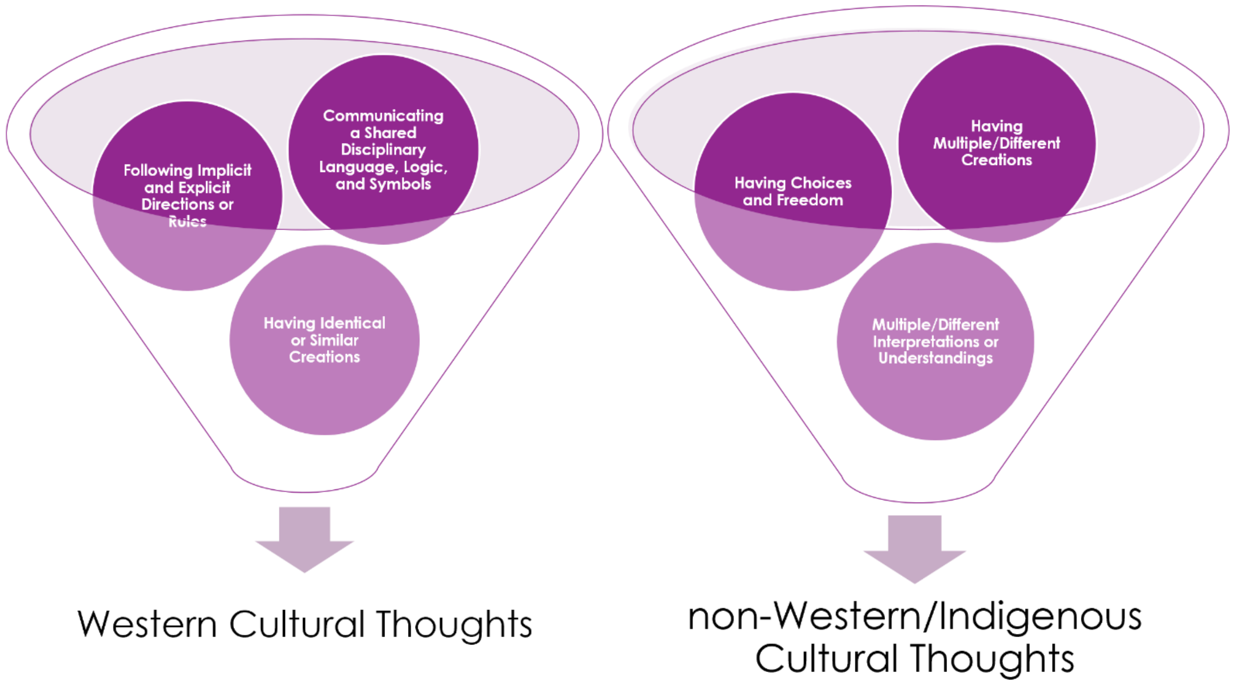
Data Reduction Protocol

Qualitative researchers are invariably confronted with exorbitant amounts of data (Guest et al., 2011; Namey et al., 2008). Therefore, having a data reduction (Guest et al., 2011; Namey et al., 2008) protocol serves the researcher well. Urquhart (2013) states "in [grounded theory methodology], we hope to get to the stage of one or two core constructs or categories" (p. 106). Despite using the various coding techniques outlined above to create the codebook, I was still confronted with a copious amount of data from which to generate CGT. Thus, I engaged in two major data reduction techniques which allowed me to gain a handle on the large data sets to create a visual model/axial coding paradigm (Creswell & Poth, 2018; Saldaña & Omasta, 2018) and a CGT that was comprehensive and parsimonious (Urquhart, 2022).

"Interpreting your data means getting creative and imaginative, so you can use your assembled materials" (Mason, 2018, p. 210) such as the researcher's codebook. Therefore, in one of the two reduction exercises, a variation of the hierarchical clustering technique (Namey et al., 2008) was applied. Specifically, all the categories that had emerged as illustrated in the codebook (see Table 2: Codebook of Science Teachers' Thought Processes) were sorted into two a priori categories: Western Cultural Thoughts (WCTs) and non-Western/Indigenous Cultural Thoughts (n-W/ICTs) (see Figure 13) based on the attributes that were established in Chapter 1. See the section: Cultural Context. For "[w]e cannot help but come to almost any research project already 'knowing' in some ways, already inflected, already affected, already 'infected' (Clarke, 2005, p. 12), but "all is data" (Glaser, 2001, as cited in Glaser, 2002). On the surface, the hierarchical clustering process appears as Figure 11. As an exemplar, Table 4 gives a more detailed view of the decision-making processes involved whereby the categories from the theme DIRECTIONS OR RULES are analyzed for the presence or absence of WCTs or n-W/ICTs. In the final analysis, all the similar variables are grouped into their respective parent/core categories to initiate the production of the axial coding paradigm (Namey et al., 2008).

Figure 11

Model of the Hierarchical Clustering Technique



Note. An illustrative example of the hierarchical clustering technique applied but does not include all categories for Western Cultural Thoughts.

Table 4

A Zoom-In View of the Hierarchical Clustering Technique for Directions or Rules

Categories	WCTs	n-W/ICTs
Following Directions or Rules	Y	N
Deviating from Directions or Rules	Y	N
Having Choices and Freedom	N	Y

Note. WCTs represent Western Cultural Thoughts, and n-W/ICTs represent non-Western/Indigenous Cultural Thoughts. Y represents Yes, and the code is present. N represents No and the code is absent.

In the second of two reduction exercises, I compared my negative/deviant case (Guest et al., 2011; Mason, 2018)—Teacher#4—to my positive cases—Teachers#1, #2, #3, and #5. Teacher#4, an International Baccalaureate (IB) physics teacher, provided the epistemological lens to make the novel insight into how culture plays a role in science teachers' thought processes. In my post-observation conversation with Teacher#4, he shared his students' struggles in understanding the IB physics textbook. Memo#3 from Teacher#4 captures attributes of the different kinds of struggle experienced by Teacher#4's students:

> MEMO#3_ American Students Have Difficulty Interpreting the IB Text
>
> DATE: 12/6/2022
> THEME: American Students Have Difficulty Interpreting the IB Text
>
> This is the first time any science teacher has directly linked culture to students' construction of scientific models. According to Teacher#4:
> (1) "CAMBRIDGE AND OXFORD WRITE BOOKS AND THEY'RE WRITTEN IN A VERY BRITISH VERNACULAR."
> (2) "JUST THEIR EDUCATIONAL PHILOSOPHY… WELL,… THE WAY THEY PUT THE THOUGHTS TOGETHER IS VERY DIFFERENT THAN THE WAY AMERICAN KIDS USE. SO I AND A FEW OTHER AMERICAN IB PEOPLE HAVE CONSOLIDATED, BASICALLY, LIKE I POST ALL MY POWERPOINTS ONLINE AND MY POWERPOINTS HAVE EVERYTHING THEY NEED, BUT IT'S FROM A TEXT THAT'S MORE GEARED TOWARDS STUDENTS THAT WERE RAISED IN THE UNITED STATES AS COMPARED TO STUDENTS THAT'RE RAISED IN THE BRITISH SYSTEM. THE EXAMPLES AREN'T DIFFERENT, … IT'S JUST THE WAY THEY WORK WITH PROBLEMS, LIKE … THEY'RE EXPECTING A DIFFERENT LOGIC THAN WE EXPECT. THAT'S WHAT I NOTICED FOR YEARS. AND I WASN'T THE ONLY ONE THAT NOTICED IT. SO IT BECOMES VERY DIFFICULT. LIKE …KIDS DON'T UNDERSTAND WHAT THEY'RE ASKING, YOU KNOW, SO WE APPROACH IT A LITTLE DIFFERENTLY. WE PREPARE THEM FOR THE EXAMS, BUT THE APPROACH … IS DIFFERENT."
> (3) "IT'S JUST THE WAY WE INTRODUCE THE PROBLEM AND THE CONCEPT IS DIFFERENT. IT'S HARD TO PUT A FINGER ON WHEN YOU WRITE IT NATURAL. IT'S JUST, … THE ANGLOPHILIC STYLE IS JUST THESE KIDS HAVE A HARDER TIME GETTING TO THE ENDPOINT."
> (4) "I NOTICED THAT OVER THE COURSE OF TIME, OUR APPROACHES, EDUCATIONAL PHILOSOPHIES IN SCIENCE HAVE DIVERGED A BIT. I GUESS IT'S THE ONLY WAY I COULD PUT MY FINGER ON IT, BUT I, YOU KNOW, DEALT WITH YEARS LIKE HAVING TO INTERPRET PARAGRAPHS AND THINGS … PUTTING IT TOGETHER AND IT'S A SLIGHT DIFFERENCE, BUT

> THESE KIDS HAVE TROUBLE, BUT LIKE JUST THE LOGIC PROBLEM AND GUESS MAYBE IT'S DIFFERENT THE WAY THEY TEACH THEMSELVES IN GRADE SCHOOL OR SLIGHTLY DIFFERENT OR DIFFERENT ENOUGH THAT THESE KIDS HAVE TROUBLE WITH IT. NOT THE CONCEPT, THE WAY THE CONCEPTS ARE TAUGHT.
> (5) “OH, THERE'S MANY WAYS TO DO IT. TRYING TO MAKE IT EASY FOR THEM.”
> (6) “THEY HAVE REAL DIFFICULTY EITHER INTERPRETING TEXT.”
> (7) “IT JUST BECAME EASIER TO TEACH THEM, I DON'T WANNA SAY AN AMERICAN APPROACH, A WESTERN APPROACH. I KNOW JUST WHAT CAME NATURALLY TO AMERICAN IB TEACHERS IN EXPLAINING CONCEPTS WHICH IS DIFFERENT THAN CAME TRUE FOR THIS PERSON EXPLAINING THE CONCEPT. APPARENTLY, I HAVEN'T A FINGER ON IT EXACTLY. I JUST KNOW THE KIDS HAVE REAL DIFFICULTY WITH THOSE.”
> (8) “SO THE ONES I USE, YOU KNOW, I HAVE MODIFIED HERE AND THERE, BUT THE ONES I USE, IF YOU GO THROUGH HERE, LIKE YOU'LL SEE, THE ORIGINAL, I THINK HE LEFT THEM ORIGINAL.” [70]

Through juxtaposing Teachers #1, #2, #3, and #5 who were all addressing students' struggles with the science disciplinary communicative norms (see Table 2: Codebook of Science Teachers' Thought Processes) with Teacher#4 who addressed students' struggles with understanding another nation's cultural communicative norms, I was able to gain insight that I was witnessing students struggling with INTER/NATIONAL CULTURE [71](Kottak, 2010, 2015) and SCIENCE DISCIPLINARY CULTURE. I have adopted the fragmented concept of INTER/NATIONAL CULTURE since students were struggling with the cultural communicative norms between two different nations. In essence, communicative norms that were struggling to cross national boundaries (Kottak, 2010, 2015). Tapping into this insight, I was able to promote SCIENCE DISCIPLINARY CULTURE as the core category/theme. See Figure 13. Since this

[70] To clarify, this is in reference to the source of the PowerPoint that has replaced the previous textbook. See an excerpt from one of the PowerPoints from Teacher#4 in Table 5.
[71] Here, I have creatively and intentionally used the slash symbol to represent (1) a literal separation between the two nation's cultural communicative norms and (2) to place a separate emphasis on national culture. In addition, still embracing the coding conventions of Saldaña (2016) and Saldaña and Omasta (2018), in this instance, the capitalization refers to the theme. This is also applicable to SCIENCE DISCIPLINARY CULTURE. See Figure 8.

was the perspective of one teacher and the project primarily emphasized New York State science assessments and standards, further exploration was beyond the scope of the project. As a result, I did not include the concept in the final theory. However, I recognized its value in the context of abductively (Bryant & Charmaz, 2019; Charmaz, 2016, 2020; Shank, 1993, November; Tavory & Timmermans, 2014, 2019; Timmermans & Tavory, 2022) interpreting the existing data.

Twists and Turns in the Changing Research Ecosystem

Several scholars refer to a dissertation study as a journey (Bloomberg & Volpe, 2018; Green & Scott, 2003; Hammond & Lester, 2021; Jones et al., 2014, 2021; Patton, 2014; Rallis & Rossman, 2012; Reichertz, 2019; Roberts & Hyatt, 2018) paved with "[s]urprises … that powers research engines" (Timmermans & Tavory, 2022, p. 1). Naturally, my thoughts and outlook shifted along the journey. However, what I have discovered, upon reflection, is that in dealing with these surprises, my role occasionally shifted along the journey. The following examples are three noteworthy experiences that exemplified the shift in my dual roles on the research journey as practitioner-researcher. Through these dual lenses, it was possible to find enjoyment in the surprises.

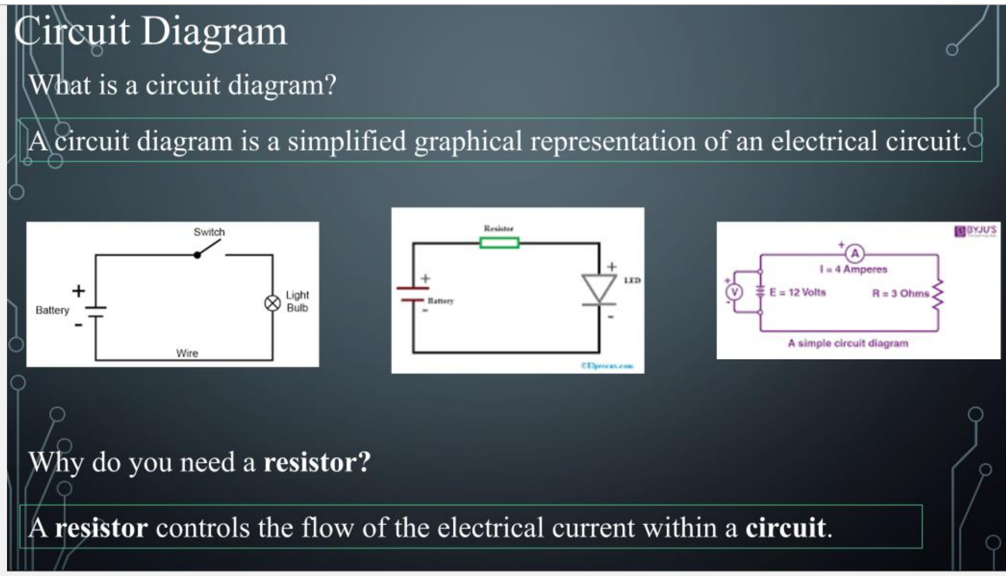
Example 1: Curious Researcher Surprised by the Missing Data

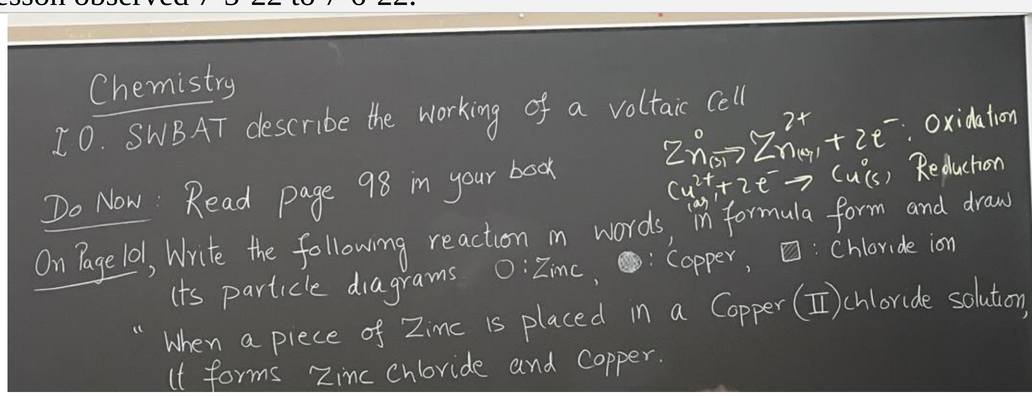
The absence of a category can be quite surprising and significant, especially if one was expected (Guest et al., 2011). In creating Figure 14: The Continua of Science Teachers' Thought Processes to provide avenues for science teachers to decolonize their assessment practices, it became evident that there was no category for plurality in communication as I had observed in themes pertaining to DIRECTIONS OR RULES, INTERPRETATION OR UNDERSTANDING, and CREATION. Thus, I became reflective on how drawings were used in the various science teachers' classrooms via the shared instructional documents and a/synchronous observations[72] instead of relying on favorable/biased interview responses (Cohen et al., 2018; Muijs, 2010). Based on the two data collection methods—document analysis and a/synchronous observation—I recognized that in each teacher's classroom, the students were given constraints[73] (i.e. rules to follow) in how the drawing should be expressed: For Teacher#1, students were introduced in a PowerPoint to disciplinary symbols for drawing circuit diagrams. For Teacher#2, the students were introduced to and provided with disciplinary symbols (vis-á-vis reference tables for writing chemical equations and teacher-generated keys of elements in drawing balanced equations for particle diagrams) in the chemistry lessons. For Teacher#3, students were provided teacher-generated symbols of water molecules and positive and negative charges that were similar to those used in the life science discipline to illustrate hydrogen bonding. For Teacher#4, students were introduced to force-body diagrams in the teacher-generated PowerPoints and were instructed to express their responses using force-body diagrams. For Teacher#5, students were instructed to use arrows to represent magnetic forces and action and reaction forces. Even the number of arrows was specified for the magnetic force diagram. See Table 5 for illustrative examples from Teacher#1, Teacher#2, and Teacher#4. In the final analysis, it was definitive that in this feature of communication—communicating shared disciplinary symbols—plurality was silenced.

[72] For this analysis, I soley relied on the data from the a/synchronous observations and document analyses instead of the data that the teachers reported during the interviews since participants are known to provide favorable/biased responses (Cohen, 2018; Muijis, 2010) in these circumstances.
[73] Here, as the arbiter of what counts as communicative success, science teachers point out what aspect of the science disciplinary culture they value in assessments.

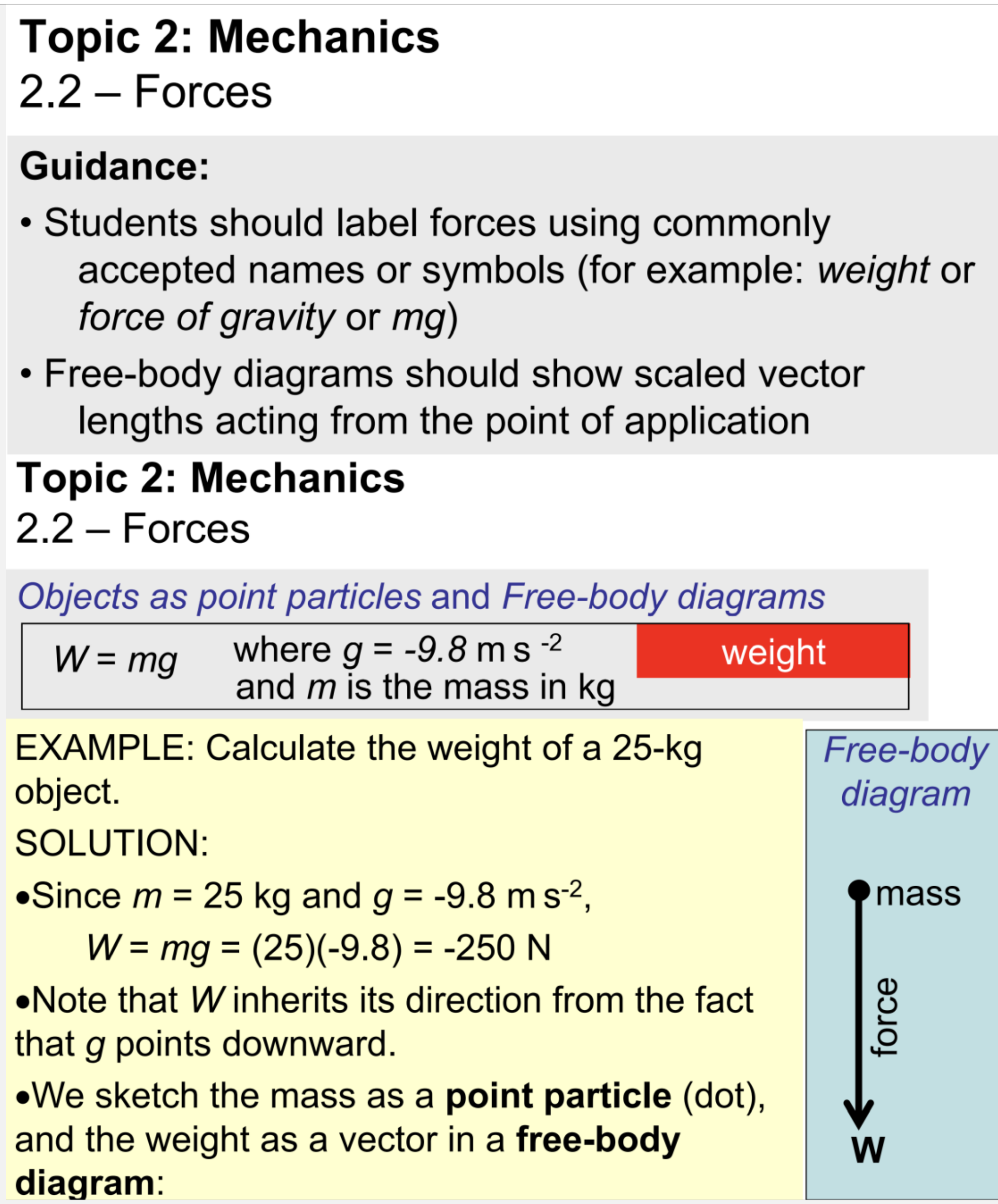
Table 5

Constraints Imposed by Disciplinary Symbols

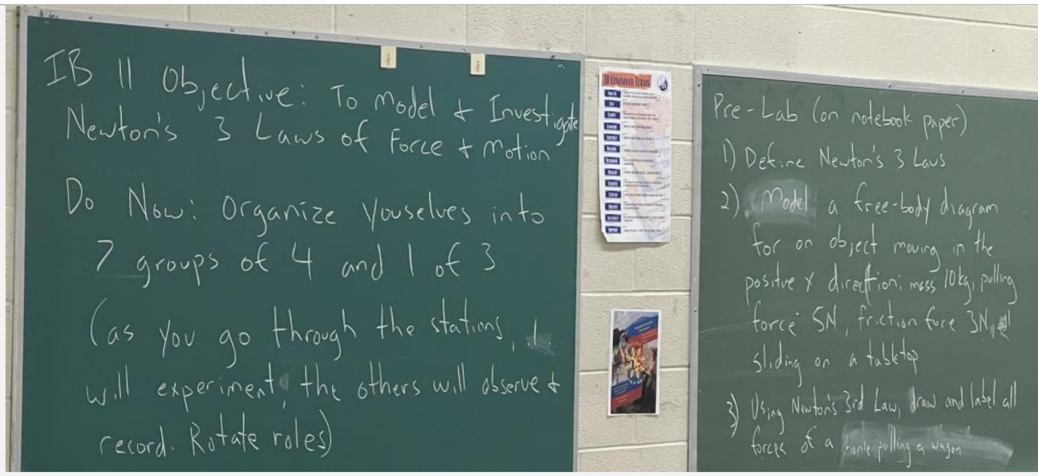
<table>
<tr><th>Teacher</th><th>Constraints</th></tr>
<tr><td>1</td><td>

PowerPoint slide with disciplinary symbols for drawing circuit diagrams from lesson observed 7-5-22 to 7-6-22.</td></tr>
<tr><td>2</td><td>

Students' directions for particle diagram with disciplinary symbols from the Chemistry Reference Tables and teacher-generated key from lesson observed 7-28-22.</td></tr>
</table>

<table>
<tr>
<td>4</td>
<td>


Introductory slides from the PowerPoint presentation on free-body diagrams for the lesson observed 11-21-22.
</td>
</tr>
</table>



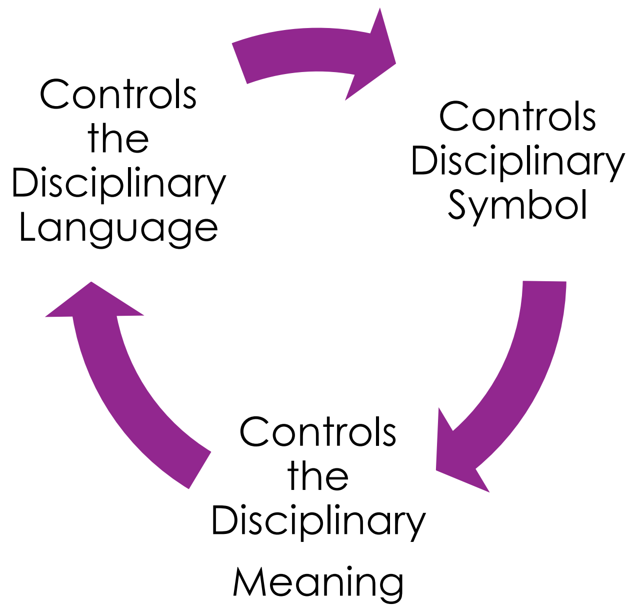
Board directions for the free-body diagrams for the lesson observed 11-21-22

Note. Illustrative examples but do not include all the teachers.

As a practitioner, this—enculturation of disciplinary symbols via silencing plural communication—made sense because students' science "cultural learning depend[s]…on the[ir] uniquely developed human capacity to use[/communicate] symbols," (Kottak, 2015, p. 18) which in science visual literacy (Barnes, 2017) has a linguistic connection (Chandler, 2017; Dunleavy, 2020), in essence, functioning as a semiotic hybrid (Lemke, 1998) requiring multimodal processes (Christidou et al., 2023). For each science disciplinary symbol is arbitrarily connected to specific language elements—words (Barnes, 2017; Chandler, 2017; Crow, 2017; Kottak, 2010, 2015). So when the constraint was initiated by the cultural disciplinary symbol, this also limited the cultural disciplinary meaning and cultural disciplinary language that students could use. See Figure 12.

Figure 12

Cycle of Enculturation



Note. The cycle shows the controlling mechanisms of the culture of science.

The mental concept (Chandler, 2017; Dunleavy, 2020) we—science teachers—call or recognize as a disciplinary symbol[74] is comprised of both an object—the signifier—and it's disciplinary meaning—the signified (Chandler, 2017; Crow, 2017; Dunleavy, 2020; Kottak, 2010, 2015). See Figure 5. This arbitrary disciplinary symbol is also arbitrarily associated with words—the disciplinary language association/that describe it (Chandler, 2017; Kottak, 2010, 2015). It is through being a part of the science disciplinary culture/community and learning the implicit and explicit rules/conventions that the meaning/relationship/ association makes sense between the disciplinary symbol and disciplinary language (Chandler, 2017; Crow, 2017; Dunleavy, 2020; Kottak, 2010, 2015), for meaning is socially constructed (Chandler, 2017; Sefa Dei, 2008, as cited in Dollie et al., 2020; Dunleavy, 2020; Gergen, 2015; Jones et al., 2014; Kivunja & Kuyini,

[74] Here, it's worth noting that signs and symbols are being used interchangeably.

2017; Kottak, 2010, 2015; Lincoln & Guba, 2013). This is the complex nature of language. In essence, imposing constraints on the disciplinary symbols also imposes constraints on the other communicative elements such as the language that we value in the science classroom. This is the mechanism science teachers leverage to impose control and make sure that communication is a two-way process (Crow, 2017)—that is, communication that is understood by both the teacher and the students. Without the imposed constraint, the communication diverges creating two communities in which "the members of one community … have difficulty in understanding the other" (Crow, 2017, p. 20). Therefore, this suggests that plurality simultaneously occurring in disciplinary symbols and language[75]—would initially create situations in the science classroom where students and science teachers struggle to comprehend each other.

Example 2: Excited to be a Practitioner-Researcher and Participant Researcher

In discussing "researcher self-as-data," (p. 108) Ellingson and Sotirin (2020) underscore that this concept includes the researcher's lived experience. Thus, as a middle school science teacher—the practitioner—I was actively engaged in testing aspects of the CGT as it was being developed, blurring the boundary (Ellingson & Sotirin, 2020) between the practitioner and researcher to create a nexus of the two identities. Memo#22 from working on Teacher#5's data summarized my adventure as a "passionate participant" (Lincoln & Guba, 2000, p. 196):

> **Memo#22_** Using the Concepts From my Theory as Mental/Formal Rubrics
> **DATE:** 1/31/23
> **THEME**: Using the Concepts From my Theory as Mental/Formal Rubrics

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[75] Here, I have not included logic because I perceive logic as a syntactic element that requires both the use of language and the symbol to show reasoning (Barnes, 2017; Chandler, 2017).

> Yesterday, in the 7-2 class, as a culminating activity, my students were creating dynamic models for one of the middle school standards addressing electric forces (see PS2-B[76]) using stop-motion animation apps or videos. Students had the choice and freedom of ways to express the model. Some students opted to represent the invisible structure and behavior of electrons produced in batteries and transported in wires using either their bodies or Barcalloo bricks (i.e. a generic brand of Legos). Others opted just to use their bodies as structures. One group chose to combine the bricks with their choreographed gestures. In evaluating the groups' completed unique models, I recognized that in order to determine if students had effectively communicated/conveyed the three elements of the standard, I needed to see and understand (1) the signs/symbols that students used to represent components that were high relevance and low/high salience components in the circuit (electrons, wires, batteries, and light bulb, respectively), (2) the meaning that students had assigned to non-conventional symbols, and (3) the logic that they were using to verbally explain the behavior of the electrons in the circuit. The class had seven groups, which produced multiple signs/symbols for the components in the circuit. Despite using different signs/symbols, I was able to understand the students' logic (i.e. the sequence of coordinated events/the choreography/reasoning/symbolic syntax) in the multiple ways they had shown their understanding. In cases where I observed thinking (confusing the symbols and language) that defied the current understanding about circuits (one group writing/saying "less negative electrons and more negative electrons" in discussing the anode and cathode of the battery), I engaged in my own clarification heuristics about the nature of charges of electrons.
>
> I think this reflection will definitely aid in mapping out my theory. This is the advantage of doing a study that is relevant to my classroom experience. The ability to test aspects of the theory in my classroom while it is in development.

As the CGT started to transform with the introduction of the subcategory ***Communicating a Shared Disciplinary Logic*** from Teacher 4,[77] I was curious to see how this new communicative feature manifested itself in my physical science classroom in a way that

[76] The NGSS standard states: "PS2.B. Types of Interactions[:] Electric and magnetic (electromagnetic) forces can be attractive or repulsive, and their sizes depend on the magnitudes of the charges, currents, or magnetic strengths involved and on the distances between the interacting objects" (Willard, 2015, p. 124).

[77] After reaching data saturation, I opted to perform a cross-case analysis (Miles et al., 2020) among the five teachers since there might have been sub/categories that emerged/recognized in later teachers that I lacked the understanding, explanation (Miles et al., 2020), and nomenclature when coding the initial cases. This supposition was applicable to the subcategory ***Communicating a Shared Disciplinary Logic*****.** In several memos from Teacher#2, attributes of this subcategory were evident. It was through juxtaposing Teacher#2 and Teacher#4, I could "pin down the specific conditions under which a finding w[as] occur[ing]" (Miles et al., 2020, p. 95).

"mirrored students' way of learning" (New York State Education Department, 2019a, p. 39). Even though I had developed its attributes from Teacher #2, #4, and #5's data sets and feverishly searched the literature to gain a deeper understanding, I sought further clarity. This revelation occurred as a two-fold process.

First, it was through juxtaposing the videos of students who had opted to use their bodies as symbols with videos of students who had made iconic symbols using the Barcaloo bricks that I had the eureka moment. Via critical reflection (New York State Education Department, 2019a), I discovered that for two-way communication (Crow, 2017) to occur, I needed to (1) recognize the alternative symbols that students had adapted as a part of their dynamic model by developing a mental blueprint for its equivalent in my "reservoir of knowledge" (New York State Education Department, 2019a, p. 11), (2) use the common disciplinary language that was shared via voice-overs as a vehicle to rapidly transfer understanding, and (3) compare the sequence of events taking place with my prior science cultural understanding.[78]

Second, in cases where the language was absent because students did not add a voice-over, I had to consult with the group to verbally share the meaning of the choreographed gestures. It was through dialoguing with the group members, learning their symbols and their meaning, and recognizing the common language we shared, that the choreographic sequence made sense. In essence, I was being enculturated into the group. See Figure 12.

Consequently, when the literature (Copi et al., 2019; Smith, 2020) describes logic as a system[79] or "chain of reasoning" (Smith, 2020, p. 1), I recognized the following: The interacting parts in the system or links in the chain were students' alternative symbols that I needed in order

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[78] This example should remind readers of The Cycle of Encultration. See Figure 12.
[79] Here, a system is interpreted as a set of interacting parts/components.

to understand the mechanism by which they interact in order to explain how a circuit works—in essence, the logic. To explicate this interaction, students used declarative knowledge (Marzano et al., 1997) via language acquired from earlier station activities (New York State Education Department, 2019a). Importantly, it was the shared disciplinary language that facilitated understanding of students' alternative symbols and allowed me to realize that we also had a shared disciplinary logic. But, it was through providing students the choice and freedom to share alternative symbols that my understanding of logic in general became crystallized. In simultaneously juggling symbols, meaning, and language, logic in science communication is also a semiotic hybrid and therefore is not purely verbal (Lemke, 1998).

Example 3: The Reflective Researcher Changing Perspective on the Journey

In a memorable experience asynchronously observing Teacher#5 that called for an interpretational pause and deep reflection, I learned/recognized that so much of what we do as science educators is implicit to our students while explicit to the teacher. Experience as members of the scientific community allows science teachers to see things that students do not (Taber, 2014). In essence, science teachers bring a different knowledge economy (Day, 2005) to the classroom that students have not yet cultivated. Often, one that cannot be reduced to FOLLOWING DIRECTIONS OR RULES, or in the parlance of Taber (2014) "following learn[ed] algorithms" (p. 4). In an experimentation-modeling lesson on drawing magnetic forces for a bar magnet as indicated by moving a compass, the following conversation between Teacher#5 and several students illustrated how implicit knowledge operates in the secondary science classroom:

> Teacher#5: *[During whole-class instruction]* "YOU'RE GONNA DRAW ARROWS TO WHERE THE NORTH IS POINTING. SO YOU'RE GONNA TAKE THIS COMPASS AND YOU'RE GONNA MOVE IT AROUND. I WANT YOU TO GO TO THE LEFT

AND TO THE RIGHT, ALL THE WAY AROUND. EVERY TIME, I WANT YOU TO DRAW WHERE THE ARROW IS POINTING NORTH. SO PUT THE… MAGNET ON THE… COMPASS AND REMEMBER YOU'RE DRAWING WHERE THE ARROW IS POINTING WITH THE NORTH. ARROW POINTING NORTH, WHERE IT'S GOING? SO YOU HAVE THE MAGNET LIKE THIS. YOU ARE SUPPOSED TO DRAW. SEE HOW THE NORTH IS POINTING FORWARD. SO DRAW AN ARROW FORWARD AND AS YOU MOVE IT AROUND THE MAGNET, SEE WHERE THE NORTH GOES."

16 minutes into the lesson:

Teacher#5: *[Addressing one student]* "YOU NEED TO SEE WHAT HAPPENS AS IT POINTS NORTH WHEN YOU GO AROUND. YOU HAVE TO DRAW WHEN IT POINTS NORTH … HOW THE ARROW MOVES AS YOU GO AROUND THE MAGNET… **LOOK AT WHAT'S HAPPENING TO THE COMPASS. SEE HOW IT'S TURNING? SO YOU NEED TO FIGURE OUT WHAT THE PATTERN IS. GOOD. PERFECT. KEEP GOING. YOU'RE DOING A GOOD JOB. .. SO JUST KEEP GOING AROUND AND … SEE HOW IT GOES.**[80] YES, GO AHEAD."

S#1: "DO WE HAVE TO TRACE THE COMPASS?"

Teacher# 5: "YOU DO NOT. YOU DO NOT. NO. YOU COULD JUST DO AN ARROW. YES?

S#2: I DON'T KNOW WHAT TO DO.

T#5: OKAY, SO HERE IS THE COMPASS, RIGHT? SO WHERE IS THE NORTH POINTING HERE? SO DRAW AN ARROW IN THAT DIRECTION… SO KEEP MOVING THE COMPASS AROUND AND SEEING WHERE IT'S POINTING NORTH.

S#3: WE FOUND OUT THAT…EVERY TIME YOU PUT WHEREVER IT GOES, THE END GOES AS WELL.

Teacher#5: SO PUT IT THE WAY YOU SEE IT HERE AND DRAW THE ARROWS.

S#4: WHAT ARE WE SUPPOSED TO DO AGAIN?

[80] In this bold portion of text, Teacher#5 has made the implicit visible for one student. The student is able to "see…, and copy…, and 'get… a feel' for what is needed" (Taber, 2014, p. 4). Thus, the student is able to cross borders between Western culture and non-Western/Indigenous culture. For observation is one of the ways in which culture is transmitted (Kottak, 2015).

Focusing solely on Teacher#5 thoughts, initially, I coded these initial verbal directions as an indicator of the subcategory ***Following Explicit Rules or Directions*** because as a member of the scientific community, I shared a ***Common Interpretation or Understanding***. In essence, I saw the lesson from Teacher#5 perspective. However, when I noticed that she was invariably repeating the rule as a ***Clarification Heuristic*** and several students were frequently expressing confusion, I recognized that the rules were implicit. Through pausing and reflecting on/systematic thinking about the experience, I was able to recognize my own biases about science instruction and gained a new understanding (Braund, 2021). With this new understanding, I was compelled to raise the question, how do science teachers know when the rules are explicit? As the early dialogue between Teacher#5 and her students clearly pointed out, it's the students' perspective that matters. If the students are frequently asking what to do or expressing confusion after multiple repetitions of the rules, then the rules as they are expressed by the teacher are implicit and need to be made explicit.

The Thought Processes of Secondary School Science Teachers

To answer the first research question (i.e., What are the thought processes used by secondary science teachers in interpreting students' scientific models that are comprised of drawing activities?), a codebook (see Table 2: Codebook of Science Teachers' Thoughts Processes) was developed. From a total of 731 codes generated in NVivo, as the codebook highlighted, five themes were revealed. They include (1) directions or rules, (2) forms of communication, (3) creations, (4) interpretation or understanding, and (5) problem-solving heuristics during students' struggles. In addition, 13 categories were revealed. They include (1) deviating from directions or rules, (2) following directions or rules, (3) having choices and freedom, (4) common forms of communication, (5) uncommon forms of communication, (6) deviating from identical or similar creations, (7) having an identical or similar creation with others or self, (8) having multiple or different creations, (9) confusing or simplifying the interpretation or understanding (10) finding a common interpretation with others or self, (11) having multiple or different interpretations or understandings (12) trying to make sense of students' struggles, and (13) using heuristics.

From the themes[81] and categories that emerged as illustrated in the codebook, nine assertions (Saldaña & Omasta, 2018) were constructed to reveal the science teachers' thoughts. See Table 6.

Table 6

Assertions Summarizing the Science Teachers' Thoughts

Number	Assertions
1	Communication indicators that students produced models that are similar/identical in creation to disciplinary others include models that showed communicative success such as communicating using shared disciplinary language, communicating using shared disciplinary symbols, and communicating using shared disciplinary logic. *Indicator:* Coded when the science teacher wrote: "SINCE THE WEIGHT AND THE NORMAL FORCES CANCEL OUT IN THE Y-DIRECTION, WE ONLY NEED TO WORRY ABOUT THE FORCES IN THE X-DIRECTION. THE NET FORCE IS THUS 50 – 30 = 20 N (+X-DIR)." *Diversity of the Category:* Disciplinary language and symbols were present in all teachers, but all three forms were present in Teachers 2, 4, and 5.
2	Students' creations (i.e., drawings) were expected to demonstrate interpretation/ understanding of specific rules/directions in order to produce drawings that were similar or identical in creation to disciplinary others. *Indicator:* Coded when the science teacher said: "LOOK AT HER FULL [a]EQUATION TO FIGURE IT OUT." *Diversity of the Category:* It was observed in *all* teachers except Teacher 5.

[81] For this calculation, I do not include the themes from the additional data reduction exercises discussed since they are not a part of the codebook.

3	When the rules/directions were explicit, students followed the rules and directions, which resulted in students producing models that were similar or identical in creation to disciplinary others. *Indicator:* Coded when the science teacher said: "YOU NEED TO MAKE SURE YOU INCLUDE THIS." *Diversity of the Category:* It was observed in *all* teachers.
4	When the rules/directions were implicit, students deviated from the rules/directions which resulted in uncommon communication, that is communication that could not be understood by disciplinary others. *Indicator:* Coded when the science teacher said: "YOU ARE NOT DOING THIS RIGHT." *Diversity of the Category:* It was observed in *all* teachers.
5	Communication indicators that students produced models that had a communicative failure and deviated from disciplinary others include models that were missing/confusing the language, missing/confusing the symbol, and or missing/confusing the logic. *Indicator:* Coded when the science teacher said: "NO IS NOT NITRATE. NO ITSELF IS A COMPOUND, NITRIC OXIDE. THAT IS NOT NITRATE ION. SO THIS IS NOT CORRECT." *Diversity of the Category:* It was observed in *all* teachers.
6	Other indicators include students confusing or oversimplifying their interpretation/understanding. *Indicator:* Coded when the science teacher said: "YOU CANNOT ADD ONE. HYDROGEN EXISTS AS A DIATOMIC MOLECULE." *Diversity of the Category:* It was observed in *all* teachers except Teacher 1.
7	There were occasions when students had the choices and freedom to create multiple drawings that are diverse. *Indicator:* Coded when the science teacher said: "ESPECIALLY WITH THAT PARTICULAR ACTIVITY, LIKE IT'S SO MANY ENDLESS POSSIBILITIES." *Diversity of the Category:* It was observed in *all* teachers.
8	Students' creations showing multiple/different interpretations were occasionally welcomed because students were communicating using disciplinary language, disciplinary symbols, and disciplinary logic that was understood by the readers/science teachers. *Indicator:* Coded when the science teacher said: "IT'S LIKE YOU'RE PUTTING A

	NOVEL IN A CLASSROOM OF 30 STUDENTS AND THEN DISCUSSING IT AND GIVING 30 DIFFERENT INTERPRETATIONS. IT'S LIKE THAT. ” *Diversity of the Category:* It was observed in Teachers 4 and 5 but not observed in Teachers 1, 2, and 3.
9	To support struggling students when the rules are implicit, science teachers employed several heuristics: (a) clarification heuristic, (b) collaborative group heuristic, (c) letter or syllable suggestion heuristic, (d) multiple-choice/guided question heuristic, (e) practice drill heuristic, (f) recognizing aesthetical appeal heuristic, (g) resembling or analogic heuristic, (h) show and tell heuristic, and (i) starting from scratch/redesign heuristic. *Indicator:* Coded when the science teacher said: [b]"WHAT IS THAT 2? 2 COPPER? 2 ZINC? CHARGE OF COPPER? WHAT DOES THAT 2 MEAN?" *Diversity of the Category:* It was observed in *all* teachers.

Note. [a] Refers to a chemical equation, a type of static drawing used in chemistry. [b]Is an illustrative example of the multiple-choice/guided question heuristic.

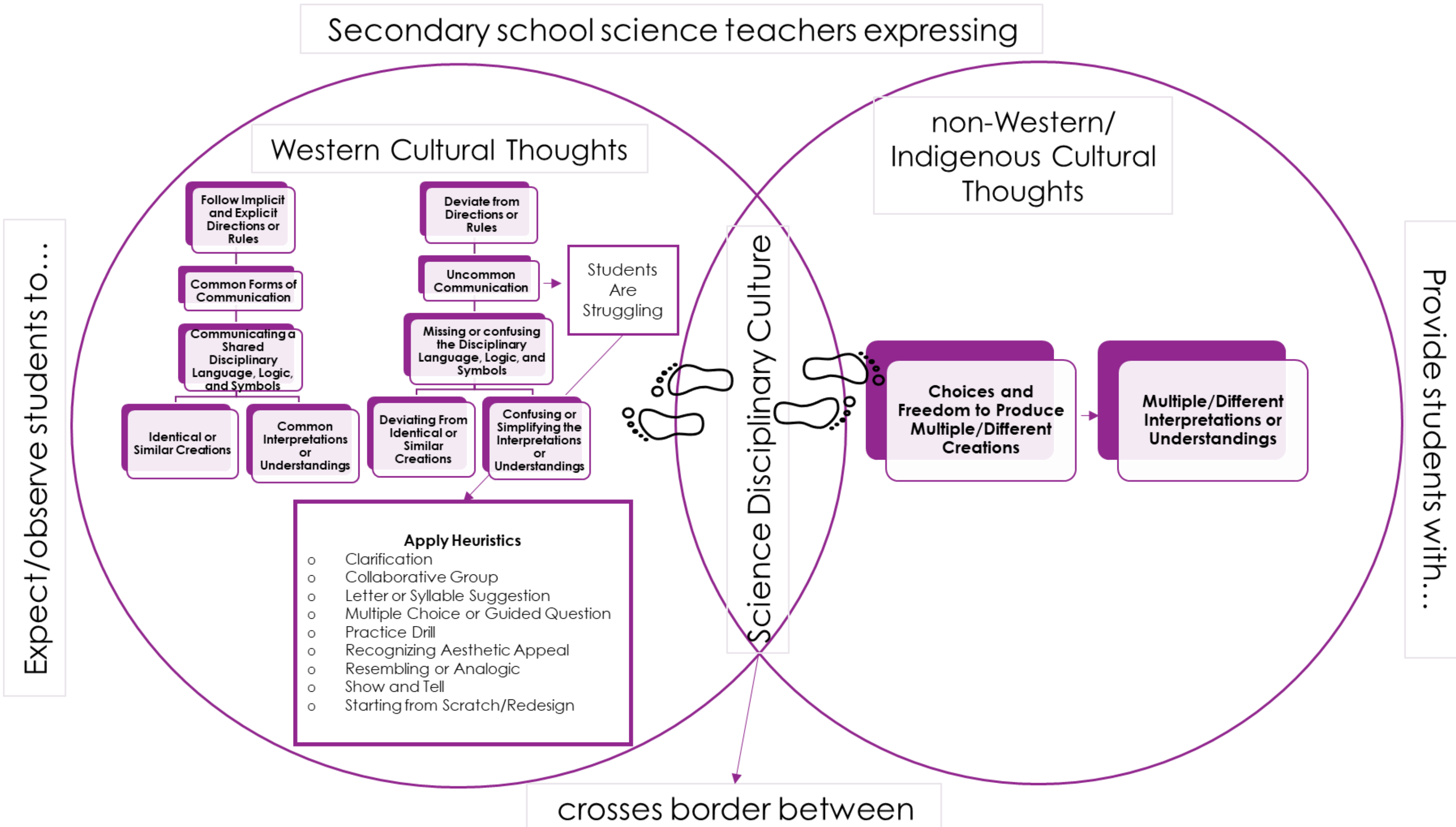
Incorporating the guidelines of Saldaña and Omasta (2018), I generated the nine assertions using a series of methodological decisions. First, based on the categories and themes that emerged from Teacher#1, six declarative statements depicting her thoughts were constructed based on the evidence-based impression (Saldaña & Omasta, 2018) I was gathering from her data. See Table 3. Second, in the subsequent data collection from Teachers #2, #3, #4, and #5, when disconfirming evidence/discrepant cases (Saldaña & Omasta, 2018) surfaced that created new categories or variants of categories, the assertion was adjusted accordingly to incorporate them until data saturation was achieved.

The Role of Culture in the Science Teachers' Thought Processes

To answer the second research question (i.e., In what way does culture play a role in secondary science teachers' thought processes when interpreting students' scientific models that

Figure 13

CGT Model of How Science Disciplinary Culture Works/Operates



Note: Constructed from inductive data from five secondary school science teachers working in lower New York State.

are comprised of drawing activities?), a diagrammatic display/axial coding paradigm (see Figure 13) and found poetry were constructed to reveal the role of culture.

Though not a traditional approach to writing a CGT, the following found poetry serves as a creative explanation of how SCIENCE DISCIPLINARY CULTURE works/operates as expressed in the secondary school science teachers' thought processes:

> In interpreting students' scientific models that are comprised of drawings, science teachers expressing Western cultural thought processes expect students to
>
> FOLLOW DIRECTIONS OR RULES,
>
> So that they can have COMMON FORMS OF COMMUNICATION,
>
> Such as COMMUNICATING A SHARED DISCIPLINARY LANGUAGE, LOGIC, and SYMBOLS,
>
> To CREATE AN IDENTICAL OR SIMILAR MODEL WITH A PEER, THEMSELVES, TEACHER, TEXTBOOK, OR REFERENCE,
>
> And also HAVE A COMMON INTERPRETATION OR UNDERSTANDING WITH A PEER, THEMSELVES, TEACHER, TEXTBOOK, OR REFERENCE,
>
> If students DEVIATE FROM DIRECTIONS OR RULES,
>
> Then the COMMUNICATION IS perceived as UNCOMMON and they are STRUGGLING,
>
> Which can be identified by students MISSING OR CONFUSING THE DISCIPLINARY LANGUAGE, LOGIC, and SYMBOLS,

Which results in students DEVIATING FROM IDENTICAL OR SIMILAR CREATIONS,

Or CONFUSING OR SIMPLIFYING THE INTERPRETATION OR UNDERSTANDING,

Which is remedied with feedback in the form of HEURISTICS: CLARIFICATION, COLLABORATIVE GROUP, LETTER OR SYLLABLE SUGGESTION, MULTIPLE-CHOICE/GUIDED QUESTIONS, PRACTICE DRILL, ANALOGIES, and SHOW AND TELL and encouragement in the form of RECOGNIZING AESTHETIC APPEAL

But when science teachers express non-Western/Indigenous cultural thought processes, students

HAVE CHOICES AND FREEDOM,

To HAVE MULTIPLE OR DIFFERENT CREATIONS,

And to HAVE MULTIPLE OR DIFFERENT INTERPRETATIONS OR UNDERSTANDINGS

Science Disciplinary Culture Crosses Border

For secondary school science teachers in lower New York State, when they interpret students' scientific models that are comprised of drawings, their thought processes reflect that science disciplinary culture crosses borders (Aikenhead & Elliott, 2010; Carter, 2011; New York State Education Department, 2019a; Rasheed, 2001, 2006; Snively & Corsiglia, 2001) between Western cultural thoughts and non-Western/Indigenous cultural thoughts. See Figure 13.

Importantly, the science teachers' thoughts also reveal that the evaluation of students' drawings operates largely across four continua[82] (see Figure 14) with themes of (1) directions or rules, (2) forms of communication, (3) creations, and (4) interpretation or understanding. In light of this understanding, these are avenues that students, science teachers, administrators, and state assessors can leverage to challenge, shape, and change the science disciplinary cultural system. As Kottak (2015) advises, "[p]eople use their culture actively and creatively, rather than blindly following its dictates" (p. 28). Thus, this continua provides several avenues or blueprints for stakeholders to decolonize secondary science assessments.

As a caveat, despite my listing aspects of science disciplinary culture as distinct phases, what I observed in the large data sets is that collectively, they operate in a complex mechanistic manner (Kottak, 2010, 2015) with multiple permutations in various science classrooms. This is critical for users of this model to recognize. Since they are deeply and historically interconnected and are invariably interacting in the science classroom, it has proven very challenging for this researcher to smoothly distinguish one from the other.

[82] Here, I provide an alternative perspective of the science teachers' thoughts as pathway for stateholders to decolonize secondary school science assessment.

Figure 14

The Continua of Science Teachers' Thought Processes

Note: * Not directly mentioned in the data but can be logically expanded to be included in the continuum on forms of communication.

Summary of the Findings

In this CGT study, using several methodological decisions, the thought processes of secondary school science teachers were identified to reflect five themes and 13 categories as illustrated in the codebook. See Table 2: Codebook of Science Teachers' Thought Processes.

These themes and categories were leveraged to construct nine assertions and an explanatory CGT found poetry that reveal the thought processes of the science teachers when they interpret students' scientific models that are comprised of drawings. In addition, these themes and categories were brought to bear in the construction of three diagrammatic displays that illustrate how science disciplinary culture works/operates in the secondary science classrooms in lower New York State. Each display spotlights various aspects of science disciplinary culture. Serving as rich data, narratives from the research trail also clarified how the inductive data was used to construct this significant body of knowledge.

CHAPTER 5: CONCLUSION

Often on the dissertation journey, scholars note that we are in the business of constructing knowledge (Jones et al., 2014, 2021; Miles et al., 2020; Silverman, 2022). In the parlance of Rhee (2021, December 7), "I am a knowledge worker." Thus, in this chapter, I chose to highlight relevant pieces of knowledge that I have constructed either through theoretical research in the literature review, the empirical findings, or learning experiences from the dissertation process that can be beneficial to others. In the first section, I share the theoretical contributions of the study which benefit science education scholars and promote additional onto-epistemological conversations in the literature. In the second section, I suggest the implications of the study for science teachers, district leaders, and state assessors. In the third section, I pose several questions for future researchers to investigate. In the fourth section, I describe two relevant limitations of the study which will be of interest to future researchers who wish to replicate the study. In the fifth section, I share how the methodological protocols that shaped the codebook development can provide methodological guidance to new CGT scholars such as dissertation candidates. Finally, in the sixth section, I reflect on my journey through the dissertation process.

Theoretical Contributions

In the literature, the field of science education has struggled to explain the cause of binary thinking behavior when teachers interpret students' scientific models (Vasconcelos & Kim, 2020). My desire to resolve this issue pertaining to the binary interpretation of students' scientific models has resulted in a significant contribution to science education research knowledge in the form of a conversation-generating theoretical literature review and several synthesized products from the inductive data. As emphasized in the theoretical literature and the synthesis of inductive data, our thoughts as science teachers are constantly being re/shaped by cultural beliefs. Therefore, our thoughts are not objective as we are trained to believe by the positivist paradigm.

First, in the literature conversation that occurs among multiple disciplines in Chapter 2, the literature review synthesizes theoretical/conceptual frameworks that show that our cultural beliefs—in science education—historically emanate from a hierarchical value placed on Western knowledge, dubbed in the science education literature as Western, Educated, Industrialized, Rich, and Democratic (WEIRD) (Rodriguez & Bell, 2018) knowledge. Therefore, our cultural beliefs are not a product of us, but rather a product of “social and structural issues” (Smith, 2012, p. 95). Using scientific models as the context to understand binary thinking, this research offers a fresh insight into a taken-for-granted problem and has made a significant contribution to science education epistemology. Specifically, from the onto-epistemological lens of scientific models, this synthesis of the literature substantially shows that the binary interpretation in science education can be traced to colonialism.

Second, in my attempt to elucidate these colonial ways of knowing that are valued in secondary science classrooms using the analysis of inductive data, the CGT highlights that, in 21st-century science classrooms, science disciplinary culture encompasses both Western and non-Western/Indigenous cultural thoughts, in essence, a convergence (Nisbett, 2003) or the crossing of borders (Aikenhead & Elliott, 2010; Carter, 2011; New York State Education Department, 2019a; Rasheed, 2001, 2006; Snively & Corsiglia, 2001) between the two cultures. For as the New York State’s Culturally Responsive-Sustaining Education (CR-S) Framework argues, culture is more than “cuisines, art, music, and celebrations [but] also include ways of thinking, values, and forms of expression” (New York State Education Department, 2019a, p. 11). It is this shared “thinking, values, and forms of expression” that my study addresses and expands our understanding of. In a significant contribution of knowledge to science education, this dissertation brought to bear five themes and 13 categories that are aptly summarized via the construction of the Science Disciplinary Culture CGT framework,[83] nine assertions, and The Continua of Science Teachers' Thought Processes to explain how science disciplinary culture works, that is, its "thinking, values, and forms of expression."

Third, the facets of the study outlined above, serve to stimulate ongoing conversations, and research and to challenge science education scholars with a positivist ontology to question accepted ways of knowing and re-examine taken-for-granted epistemology using an interdisciplinary approach.

Implications for Stakeholders

This study provided several useful findings that can benefit all stakeholders involved in science education. The challenge for science education stakeholders is where to start. In other words, at the classroom level, what instructional and assessment adjustments can science teachers make to support students in crossing borders (Aikenhead & Elliott, 2010; Carter, 2011; New York State Education Department, 2019a; Rasheed, 2001, 2006; Snively & Corsiglia, 2001) between Western cultural knowledge and non-Western/Indigenous cultural knowledge? In addition, how can district leaders support teachers as practitioner-researchers and benefit from the study? Finally, how can state assessors re-imagine scientific model assessment?

Science Teachers

In secondary school science classrooms, far too much of science instruction fails to make

---

[83] Here, the framework includes both the diagrammatic display and accompany explanation of the found poetry.

explicit the knowledge that we teach (Taber, 2014) and this Western cultural approach has proven to have real consequences (New York State Education Department, 2019a) in physical science education (Fokides & Papoutsi, 2020; Taber, 2014). As one of the assertions from my CGT emphasizes, *when the rules/directions were implicit, students deviated from the rules/directions which resulted in uncommon communication, that is communication that could not be understood by disciplinary others*. This implies that the conceptual application[84] (Brown, 2017; Penuel et al., 2017) of this assertion allows teachers to efficiently and effectively make evidence-based predictions about the cause of communicative failure. In this instance, the cause is a communicative failure emanating from science teachers' use of implicit rules/knowledge rather than their use of explicit rules/knowledge (Taber, 2014). Therefore, in a diverse science classroom, *heuristics* designed to counteract students' communicative failure must be strategic—effective, efficient, and equitable.[85] Merely *applying any heuristic when students are struggling* is ineffective and inefficient. Instrumental application[86] (Brown, 2017; Penuel et al., 2017) of the *three forms of communication, disciplinary language, disciplinary logic, and disciplinary symbols that were used to evaluate students' drawings* and their attributes as exemplified in the codebook is crucial in making the implicit rules/knowledge visible. As illustrated by the CGT, these are the types of science disciplinary cultural knowledge that are valued in the secondary science classroom.

It is also important to show our students how to cross borders between WCT and n-

[84] In this respect, I perceive a conceptual application as one where the science teachers leverage the study to inform or guide their thinking (Brown, 2017; Penuel et al., 2017).
[85] According to Brown (2017), "effective[ness], equitabl[ility], and efficien[cy]" (p. 37) are three metrics of successful implementation of evidence-informed practice.
[86] In this respect, I perceive an instrumental application as one where science teachers adopt (Penuel et al., 2017) the three common forms of communication as tools for instructional use.

W/ICT to access the culture of power (Delpit, 2006) as it is currently manifested in science assessments.[87] As it stands, what is the most effective way to foster students' crossing borders (Aikenhead & Elliott, 2010; Carter, 2011; New York State Education Department, 2019a; Rasheed, 2001, 2006; Snively & Corsiglia, 2001) between Western culture and their other ways of knowing? What this research concretely elucidated is that implicit knowledge cannot be lectured, and it is not easily conveyed in textbooks as illustrated by the participants. As portrayed in an interaction between one of the participants and a student, it must be observed, imitated, comprehended, and practiced (Taber, 2014).

In addition to the recommendations outlined above, another good starting point for science teachers is provided in Figure 14: The Continua of Science Teachers' Thought Processes for it provides science teachers with achievable and practical advice in the form of (1) tools for effective inclusive feedback to students without preference for a dominant knowledge system (New York State Education Department, 2019a), (2) a pedagogical lens to reflect on their instructional practice to stimulate innovative learning (New York State Education Department, 2019a), (3) a framework to design and evaluate assessment products that encourage pluralism (New York State Education Department, 2019a) for scientific models, and (4) an idea generator that can spark many creative classroom projects (New York State Education Department, 2019a) once science teachers have the opportunity to interact with all this research has to offer.

For secondary school science teachers—like myself—who are seeking an equitable, efficient, and effective tool for evaluating plural creations of scientific models that are comprised of drawings, test a student-friendly version of Figure 2: Theoretical Model of Drawing Activities

[87] This claim is made based on the sample released NYS science assessments that lack multiple forms of expression (CAST, 2018) of scientific models that are comprised of drawings.

Proficiency in your classrooms. The theoretical model is adaptable to any science disciplinary topic and is more equitable than using binary thinking to evaluate students' scientific models.

Despite the many possibilities provided by the CGT and theoretical literature synthesized model, ongoing research is needed in this area to further explore how secondary science teachers make implicit information visible in the classroom environment and evaluate students' scientific models that are comprised of drawings. In essence, how do we decolonize science instruction and assessments using the three forms of communication, the types of directions and rules, students' creations, and students' interpretations or understandings typically encountered in secondary education science classrooms?

District Leaders

"Educational research is greeted with suspicion both within and outside of the academy" (Ladson-Billings, 2021, p. 19). From personal experience on the research trail, I wholeheartedly concur with Ladson-Billings (2021). Recruiting teachers for this research project was the most discouraging aspect of this project. As the gatekeepers to the science teachers, district leaders can delay or deny access to research in the science classrooms (Brown, 2017; Cohen et al., 2018). It is understandable that district leaders fear negative publicity. However, district leaders must be cognizant that practitioner-researchers are uniquely positioned in the classroom to know the pedagogical issues that they are facing, sometimes years before it is recognizable to district officials. The type of professional development that can solve these problems cannot be acquired from a one-hour, one-day, or one-week workshop. The issues are so complex that only years of study using the interdisciplinary tools from a dissertation can solve them. Therefore, I challenge district leaders to support science teachers to conduct dissertation research in their science classrooms and across their districts to improve their pedagogy. Give them "the agency, space, and tools to grow and thrive as scholars of their professional practice" (Tangredi et al., 2021, p. 47). In essence, district leaders, support science teachers to connect their professional experience with research practice so that they foster a pedagogical culture that frequently critically assesses their practice (New York State Education Department, 2019a). One way to accomplish this is by forming partnerships (New York State Education Department, 2019a) with universities to support these types of investigations and fast-track the district's IRB process. Once this foundation has been established, form a network of science practitioner researchers that can support the district's endeavors in improving science instruction via practitioner-researcher-based expertise and fill the gap between science education researchers and science practitioners (Farley-Ripple, 2021; New York State Education Department, 2019a).

Moreover, district leaders can benefit from this research by leveraging Figure 14: The Continua of Science Teachers' Thought Processes in evaluating and adopting/adapting science curricula. They can privilege curricula, instructional methodologies, and assessments that decenter the dominant ideologies and "mirror… students'[multiple] ways of learning, understanding, communicating, and demonstrating curiosity and knowledge" (New York State Education Department, 2019a, p. 39). In addition, they can share the CGT diagrammatic display, found poetry, and nine assertions with stakeholders to initiate/continue the conversation to decolonize current science practices in their districts (New York State Education Department, 2019a).

New York State Policymakers

In 2019, via the CR-S Framework, the state shared its commitment to improving science learning results by "educat[ing] all students effectively and equitably, as well as provid[ing] appropriate supports and services to promote positive student outcomes" (New York State

Education Department, 2019a, p. 7). My study aims to bridge the state's CR-S vision and guidelines with the NYSSLS addressing scientific models by providing assessment writers with a better understanding of scientific models that are comprised of drawings. To support students in achieving positive student outcomes on the new assessments to be implemented in 2023-2024 (New York State Education Department, 2021), assessment writers must be cognizant of communicative demands, specifically, disciplinary language, symbols, and logic that students must explicitly share on assessments and these should be considered in rubric development. Thus, in using my research which is illustrative of the current understanding of scientific models in their decision-making, NYS policymakers would be making an evidence-informed policy (Brown, 2017; OECD Centre for Educational Research Innovation, 2007). With this current understanding of the communicative expectations in secondary science classrooms, policymakers are better positioned to make informed decisions rather than relying solely on intuition (Brown, 2017). In addition, I challenge assessment writers to design inclusive assessments (New York State Education Department, 2019a) that allow students to show their multiple ways of expressing scientific models that are comprised of drawings (CAST, 2018). One recommendation is the use of science modeling portfolios that can be assessed using a student-friendly language version of Figure 2: Theoretical Model of Interpreting Drawing Activities Proficiency.

Future Researchers

Though this CGT research provided a more in-depth understanding of secondary school science teachers' thought processes of students' scientific models that are comprised of drawings, still several avenues exist for future research. The CGT identified nine assertions that described the science teachers' thought processes that require validation via the construction and testing of a quantitative measure such as a science disciplinary culture survey.

Furthermore, additional research is needed to understand how the three forms of communication—language, logic, and symbol—operate in making scientific knowledge/rules explicit and implicit. Other questions that should be explored include:

1. What are secondary school teachers' thought processes in interpreting other types of scientific models such as flow charts/concept maps or gestures?
2. What are students' thought processes in constructing scientific models that are comprised of drawings?
3. Since the study was conducted using secondary school science teachers from one district in lower New York State, how do the findings compare when the study is replicated in another district, state, or in a lower-grade band?
4. How effective is Figure 2: Theoretical Model of Interpreting Drawing Activities Proficiency for evaluating drawing activities?
5. On science formative assessments, how effective is feedback that uses the communicative norms of language, logic, and symbols?
6. How does the CGT facilitate the generation of feedback for students that promotes inclusivity and fosters innovative learning in secondary science classrooms?
7. Teacher#4 noted that IB physics textbooks are written using a different type of logic. In a thematic and content analysis of IB textbooks, what communicative patterns are revealed?

8. Since the study did not include any earth science educators, what patterns are revealed when earth science educators interpret students' scientific models that are comprised of drawings?
9. Teacher#1 used a low-fidelity static drawing activity for teaching a unit on circuits. How does the use of low-fidelity static drawings compare with traditional static drawings in students' acquisition of science disciplinary communicative norms: language, logic, and symbols in secondary school science classrooms?
10. How is logic manifested in the different secondary school sciences?
11. How is logic related to enculturation?
12. Teachers#2 and #4 shared that learning chemistry and physics is like learning another language. How do secondary school science teachers efficiently, effectively, and equitably leverage strategies for second language acquisition in physical science classrooms to facilitate students' learning outcomes of physical science disciplinary core ideas?
13. Data from Teachers#1 and #2 suggests that secondary school chemistry and physics teachers interpret electricity generation differently. Is this epistemological pluralism common in the general population of physical science educators?

Future CGT Scholars

Though this study's primary aim was to develop a CGT for science education that explained the thought processes of science teachers when they interpret students' scientific models, in the process, I have also made a significant contribution to grounded theory methodology in the form of a codebook development protocol for dissertation candidates seeking concrete methodological strategies. These methodological strategies include (a) a transcript protocol for scholars that would benefit from transcripts that closely reflect written language, (b) using sensitizing concepts as a priori data as an initial methodological orientation point for candidates in the field, (c) a technique for scholars who want to make the methodological leap from a pilot study to a larger scale study, (d) a model for approaching coding for new scholars seeking methodological steps, (e) a literature integration approach for those who seek methodological guidance when this need does arise, (f) a mechanism for tentatively theorizing for new researchers whose goal is to produce methodological assertions, (g) data reduction protocols for methodological scholars seeking a goal of one to two categories, and (h) the incorporation of the frequency table that allows the codebook to cross borders between qualitative and quantitative research (Creswell & Creswell Báez, 2021) for scholars who seek to gain acceptance in both research communities.

It's important to note that these methodological processes are not unique to my study. They were only possible because I "[stood] on the shoulders of [methodological] giants" (Newton, 1675). However, what my study does effectively and efficiently is to provide a tangible audit trail into the codebook development via the above-outlined methodological decisions which can be traced back to a visible codebook. Often, codebooks are a mystery in published GT studies which are methodological criteria of GT success since codebooks are not often provided (Creswell & Creswell Báez, 2021). Therefore, new scholars—like myself—who seek methodological guidance to solve a problem of practice, are left in the dark and are compelled to discover their own approach.

Limitations of the Study

The study has two relevant limitations pertaining to context and response bias that are worth considering. With respect to context, since the study was conducted with only five participants from one district in lower NYS, I do not know the extent to which the findings are generalizable/transferable to science teachers in other districts in NYS, in other states, and in the rest of the country. Hence, this study lacks external validity/transferability in terms of the different contexts in which secondary school science teachers in the United States teach (Bergin, 2018; Cohen et al., 2018; Jones et al., 2014, 2021; Saldaña & Omasta, 2018). To truly capture wider generalizable findings would require collecting representative samples from districts across the United States which were beyond the scope (Saldaña & Omasta, 2018) and financial means of this exploratory CGT study with the primary aim of achieving an in-depth understanding of a novel central phenomenon until data saturation (Creswell & Poth, 2018; Davoudi et al., 2016; Jones et al., 2014, 2021; Patton, 2014; Urquhart, 2022). Nonetheless, the pursuit of an investigation that seeks a broader understanding is worthy of future quantitative study.

In the study, three methods of data collection were employed to garner data for coding: a/synchronous observations, document analyses, and online interviews. It is important to repeat that for the semi-structured interviews, participants were emailed the interview questions in advance to prepare responses and to facilitate the completion of the interview in a manner that was respectful of their time. This was also documented in the LIU IRB Research Consent Form. Keeping the interview protocol in mind, as addressed in Chapter 4 in the section Example#1: Curious Research Surprised by the Missing Data, I have treated the interview responses as self-reported data, that is, data subjected to response bias (Cohen et al., 2018; Muijs, 2010). Therefore, I abductively infer that the interviews produced a strong cultural bias for categories pertaining to diversity in DIRECTIONS OR RULES, INTERPRETATION OR UNDERSTANDING, and CREATION, but not the categories pertaining to diversity in FORMS

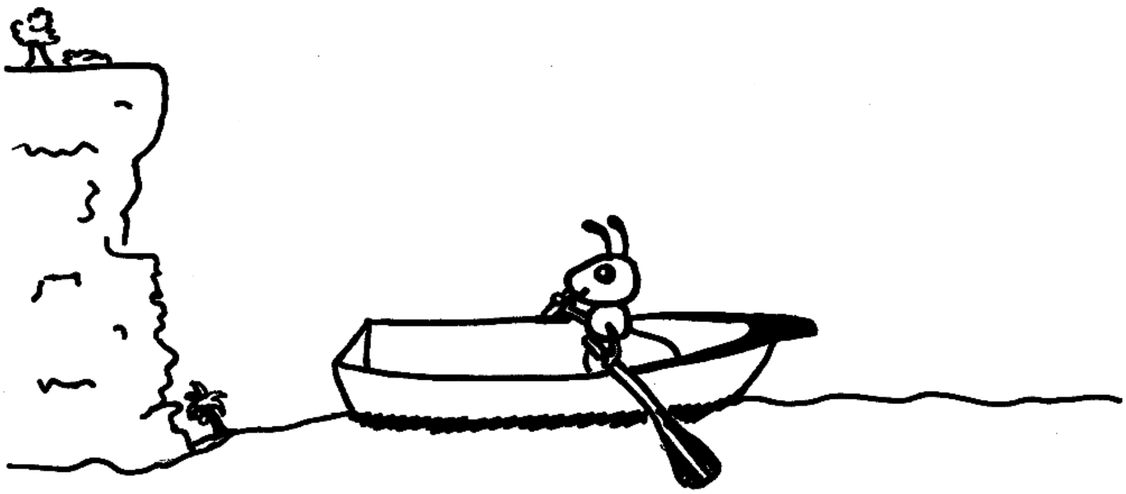
OF COMMUNICATION. Currently, in NYS, there is a shift in policy for science educators to integrate decolonizing or culturally relevant pedagogical strategies in their classrooms, and that policy change is reflected in the participants' interview responses. However, the use of other data collection methods—observations and document analyses—mitigated the response bias as alluded to in Example#1: Curious Researcher Surprised by the Missing Data. In spite of the response bias mitigation methods, the impact of the advanced preparation (Cohen et al., 2018)—using the emailed questions—is one that is worthy of future investigation which can subsequently be statistically compared with the current study.

Personal Reflection

So now that the journey is drawing to a close, I reflect: How did I get here? The single most important ingredient for starting and completing the dissertation is having a compass. Rodgers (2022, November 7) defines a *compass* as "a device that indicates direction. It is one of the most important instruments for navigation" (Compass section, para. 1). Anyone who knows me well, will confirm that I believe in having a backup device or a contingency plan for everything I do. For my journey, I had a personal compass—the desire to no longer be underestimated—and a professional compass—the desire to improve my professional practice. Thus, when the journey ostensibly appeared impossible, I would often take out one of my two compasses to guide me. I would also repeat my personal aphorism "You can do this Redway!," to eradicate any negative thoughts. For on this remarkable yet arduous journey, I have often seen myself as an ant on a canoe in the middle of a tumultuous ocean—navigating my way to land. For in my imagination, grounded theory was my canoe, the dissertation process was the ocean, and completing the dissertation was safely reaching land.

Figure 15

Ant on a Canoe



Note. S.S. Ranginwala, illustrator

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Appendix A: Survey Questions

1. *Content Expertise/Knowledge*: How long have you been teaching using scientific models?
2. *Static and Dynamic Drawing Activities*: What specific types of scientific models do students construct in your classroom?
3. *Science*: What science topics or core ideas do you address when using scientific models?
4. *Language*: What language(s) do you speak? If applicable, what is your dominant language?
5. *Ethnicity*: What is your ethnic identity?
6. *Race*: What is your racial identity?
7. *Gender*: What is your gender identity?

Appendix B: Observation Protocol[88]

T#:__ Date: Time: Length of the Observation:	
Descriptive Notes (Actions, Reactions, Interactions; 5Rs: Routines, Rituals, Rules, Roles, and Relationships[89]) I notice… Said… Wrote…. Did…	Reflective Notes (Reason, Motive, Purpose, Objective, Goal, Intention) I wonder… I am surprised that…. This is similar to…. This is different from…
Sketches	Reflective Notes
	I wonder… I am surprised that… This is similar to…. This is different from…
Questions	Reflective Notes
How… What… Why…	I wonder… I am surprised that… This is similar to…. This is different from…

[88] Observation protocol was designed using literature review from respected scholarships (Creswell & Creswell Báez, 2021; Rossman & Rallis, 2017; Saldaña & Omasta, 2018; Timmermans & Tavory, 2022).
[89] "[P]ay attention to sequence" (Timmermans & Tavory, 2022, p. 60) during interactions.

Appendix C: Document Analysis Protocol with Visuals[90]

Participant's Teacher#:

Analyst: Alecia Redway

Date:

Name of the document:

Author:

Format:

Pages for Analysis:

Science Core Idea Addressed:

1. What is present and what is absent in the scientific model?
2. How am I limited in interpreting this scientific model?
3. What meanings are preferred by this scientific model?
    a. What is the dominant meaning embedded in this scientific model?
4. What results from the examination of the symbols and codes in the scientific model?
5. What are the realistic, representative, and ideological signs embedded in the scientific model?
    a. How is the scientific model encoded in cultural codes?
    b. How do the representative symbols work together to encode a preferred meaning? What is the preferred meaning?

[90] Questions are adapted from "Cultural Studies Theory: The Production and Consumption of Meaning," by V. O'Donnell in S. Josephson, J. D. Kelly, & K. Smith (Eds.), *Handbook of Visual Communication: Theory, Methods, and Media* (2nd ed., pp. 203-218), 2020, Routledge. Copyright 2020 by Routledge.

6. What meaning can different viewers make of this scientific model? In the scientific model, what is the dominant meaning? In the scientific model, what meanings are possible from negotiations? In the scientific model, what meanings might be resisted or opposed?
7. How might the decoded meaning give the science teacher a sense of power? How is this related to the science teacher's social identity?
8. What is at stake in the representations that are used in the scientific model?

Reflection Notes:

1. ..
    a. ..
    b.
2. ..
    a. ..
    b. ..
3. ..
    a. ..
    b. ..
4. ..
    a. ..
    b. ..

Appendix D: Document Analysis Protocol without Visuals[91]

Participant's Teacher#:

Analyst: Alecia Redway

Date:

Name of the document:

Author:

Format:

Pages for Analysis:

Science Core Idea Addressed:

1. What are signs of rules for thinking[92]?
2. Given the context and cultural knowledge of… what other signs of culture are visible[93]?
3. Given the context and cultural knowledge of….what signs of culture are invisible[94]?
4. What are signs of power dynamics[95]?
5. What are signs of binary/plurality of knowledge[96]?
6. What does the text suggest about the author's attitude, values, or beliefs[97]?
7. What does the text suggest about the science teacher's attitude, values, or beliefs?

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[91] From a pilot test conducted in Fall 2020 consisting of one participant, these questions were generated based on themes revealed during the pilot test.

[92] Rules for thinking is one strategy that I will implement to address latent knowledge (Boyatzis, 1998; Saldaña & Omasta, 2018).

[93] Factors of visibility is an example of one approach that I will use to handle manifest cultural knowledge (Boyatzis, 1998; Kenny & Fourie, 2015; Saldaña, 2016; Saldaña & Omasta, 2018)

[94] Invisible will be interpreted as "silences, gaps or omissions" (Rapley, 2018, p.123) for each document.

[95] Look for power of number—statistics, issues of authority, control (Rapley, 2018)

[96] Binary knowledge will tackle issues of objective epistemology and plurality of knowledge will address subjective epistemology (Carter, 2011).

[97] As stated in the document analysis section, manifest and latent contents are revealed through "values, attitudes, and beliefs" (Saldaña & Omasta, 2018, p. 105).

8. Who does the text encourage to speak? Who does it silence? How is this accomplished?[98]

[98] To further elicit other power dynamics from the text, Silverman, 1987, as cited in Rapley, 2018 notes “power can work as much by encouraging persons to speak, as by silencing them” (p.121).

Appendix E: Interview Protocol[99]

Interview protocol: How do secondary school science teachers interpret students' scientific models that are comprised of drawing activities?

Time of the interview:

Date:

Place:

Interviewer: Alecia Redway

Interviewee:

Position/Grade of the Interviewee:

Description of the study: The purpose of this study is to develop a constructivist grounded theory that explains the processes used by secondary school science teachers to interpret students' scientific models that are comprised of drawing activities.

Interview questions:

Background Questions:

1. How did you acquire your knowledge about model-based instruction (MBI)?[100]
2. Tell me about how you are currently using scientific models in your classrooms. *Clarifying questions for 2:* How often?
3. Tell me about the reason you shifted to an MBI approach.

Background Reflection Notes:

1. ..

---

[99] In Fall 2020, the interview protocol was pilot tested with one participant and has been subsequently revised based on further literature review and the researcher's experience with the questions.

[100] Added after the pilot based on interaction with participant.

2. ..

Participant Observation:

Using the samples of student work that you have provided, I would like you to describe your thoughts on how you would evaluate each model.

Participant Observation Follow-up Questions:

1. What is the purpose of the model that you are about to discuss[101]?
2. How do you determine what are acceptable/ reasonable, or correct answers from students? *Ask participants as a 2 part question. Clarifying questions for 2[102]:* What factors are given priority in determining acceptable/reasonable answers? What scientific principles do you expect to see in the students' scientific models?
3. What conventions/norms/rules[103] do you expect to see in students' models?
4. When interpreting students' scientific models, what are some concerns that you have?
5. In grading students' scientific models, what typical signs/symbols are visible to receive the *best score*? Can you give me an example? Describe for me, what makes the response ideal. What else do you look for? Why is…relevant?

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[101] In studying Chinese chemistry teachers' application of MBI, Wang et al., 2014 note that science teachers primarily focused on using models to facilitate students' understanding of content instead of developing thinking skills. I believe that teachers who perceive the purpose of models as to develop content will see scientific model construction as binary—wrong or right, while teachers who perceive the purpose of models as developing thinking skills or inservice of making sense of systems and phenomena (Passmore et al., 2017) will see scientific model construction as plural—accepting multiple representations.

[102] I adapted these clarifying questions from research questions and results investigated by Wang et al., 2014 in the study of Chinese chemistry teachers' selection of pre-existing models for classroom instruction.

[103] This question along with several other questions in the interview illustrates several attributes of culture as addressed Chapter 1: My Approach to Culture. These questions exemplify how I embed the literature in their production. Originally phrased as "what cultural norms do you expect to see in students' scientific models? in the pilot, this question was subsequently revised to express attributes of culture to mitigate participants' confusion.

6. In grading students' scientific models, what typical signs/symbols are in/visible to receive a *poor score*? Can you give me an example? Describe for me, what makes the response poor. What else do you look for? Why is…irrelevant?
7. The instructional ancillaries that you shared earlier, how do they support your use of MBI?[104]

Say: Thank you for participating in this interview. Please note that your responses are confidential and only will be shared with members of my dissertation committee and peer reviewers. May I contact you for potential future interviews?

Participant's Observation Notes (*What stands out?)*

Participant Observation Follow-Up Questions Reflection Notes:

1. ..
2. ..
3. ..
4. ..
5. ..

[104] Serving also as a reminder to connect the document analysis to the interview, this question seeks to gain a handle on material culture (Rapley, 2018) in these cultural repositories (Higgins, 2016).