RETHINKING MULTIMODALITY, LANGUAGE, AND MODELING PRACTICES IN KNOWLEDGE BUILDING IN SCIENCE

by

AYÇA KARAŞAHİNOĞLU FACKLER

(Under the Direction of Daniel K. Capps)

ABSTRACT

The field's work on modeling practices falls short of encouraging learners to use their lived experiences and leverage their linguistic resources while engaging in science practices. Conceptualizing modeling as a multimodal practice in which diverse language resources are welcomed and encouraged in knowledge building, this qualitative case study focused on how multimodal modeling practices could help learners, in this case, 10 preservice elementary science teachers, build knowledge as they engaged with a complex science topic by leveraging their linguistic resources. The research questions guiding this study were: How did multimodal modeling practices facilitate packing and unpacking meanings in knowledge building in science? In what ways did multimodal modeling practices play a role for learners in their switching between everyday language and scientific language in knowledge building in science? How did multimodal modeling practices influence learners' understanding of models and modeling in knowledge building in science?

Data sources included video and audio recordings, student artifacts (drawings, reflective essays, and modeling worksheets), student interviews from a classroom implementation of a modeling curriculum in a science methods course at a research university in the southeastern part of the United States. Adopting an interdisciplinary perspective to data analysis, this study combined Multimodal Interaction Analysis (MIA) and the semantics dimension of Legitimation Code Theory (LCT) to examine how preservice teachers use a variety of semiotic resources for a range of meaning-making moments.

The findings of this study suggested that multimodal modeling practices (i) facilitate embodied interactions between learners, learning materials, and linguistic resources that help pack and unpack meanings, (ii) encourage the development of a shared, intermediate language that helps learners move from disembedded ways of thinking and speaking to embedded ways of thinking and speaking in science learning, and (iii) expose learners to a better understanding of what meaningful and equitable modeling practices might look like in classroom settings by showing them what models are, who can develop a model, and whose knowledge contributes to modeling practices while building knowledge in science. Implications for research and practice and suggestions for future research directions were explored.

INDEX WORDS: Modeling, Multimodality, Legitimation Code Theory, Semantics, Case Study, Preservice Teacher Education

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DEDICATION

This dissertation is dedicated to me, who spent the last fifteen years dreaming of becoming a doctor, and to my son, Ege Carl–may you never stop learning.

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CHAPTER 1

INTRODUCTION

Brief Overview of the Problem Addressed in This Dissertation

The problem addressed in this study is that there is too much emphasis on the academic language of science in science learning. Science teachers tend to prioritize the use of scientific language by their students to make sense of ideas while undervaluing diverse language resources (e.g., gesture, gaze, or sound) that their students bring to classrooms. This may create a barrier for students to engage in disciplinary practices in science. Students need a space for incorporating their familiar ways of communicating into their science learning to have a meaningful learning experience and easy access to scientific ideas that they learn. This study suggests that one way of providing a solution to this problem is using what I call multimodal modeling practices. Multimodal modeling refers to the practice of modeling in which multimodality is an important aspect of both the process of developing a model and the product itself (the model) rather than a trivial add-on. Multimodal modeling practices welcome and encourage diverse language resources generated and used by students while making sense of science ideas. This multimodal lens supports an investigation into meaningful and rich meaning-making that emerges in modeling practices, which has not been a focus of research in science education. The overarching purpose of this study is to examine the language generation functions of multimodal modeling practices to create a bridge between everyday language and scientific language to promote linguistic equity in science classrooms. While the cultural and linguistic background of each student varies, the uniting factor in multimodal modeling practices is that it values and encourages diverse ways of knowing and communicating through disciplinary practices in science. Multimodal modeling practices also help students create a language for science rather than prioritizing only the use of scientific language in knowledge building. To promote such linguistic equity in science classrooms, science teachers should enhance their knowledge of and skills in implementing meaningful and equitable modeling practices. One way of accomplishing this goal is to realize that science teachers need opportunities to learn the same way students learn. With this in mind, this study examines how multimodal modeling practices could help preservice elementary science teachers to build knowledge as they engaged with a complex science topic by leveraging their linguistic resources.

Overview of the Dissertation

This dissertation is organized into five chapters. In Chapter 1, I introduce the problem this study addresses, its purpose, the research questions, my positionality statement, and the definitions of key terms. In Chapter 2, I present the literature review and theoretical framework of the study. The literature review is organized into two sub-sections: (a) learning with models and modeling in science education and (b) learning through multimodality in science education. As the theoretical and analytical framework, LCT semantics, explains the construct, semantic density, which I work with in this study. In Chapter 3, I introduce the study design, site, and participant selection. I also provide thick descriptions of the model-based lesson materials and activities that were used in the study. I then describe the data collection procedures and analyses, and the limitations of the study. In Chapter 4, I report the findings and my interpretations with respect to the research questions. In Chapter 5, I provide an overall interpretation of the findings, discuss the scholarly contribution of the study, report implications for research and practice, and suggest future research directions.

Problem Statement

Teacher: When a bird finds a worm, it grabs it by its tail. Worms are hard to pull out of the soil. The worm anchors itself in the ground with its bristles and pulls back hard with its powerful muscles. So as the bird is pulling the worm, the worm's other end is kind of doing what?

Student: The worm's grabbing onto the dirt.

Teacher: It's kind of grabbing. It's like suctioning itself.

Student: [Makes a suctioning sound.]

Teacher: To the bottom of the dirt, or bottom of, you know, under the ground. So that if the. . . as the bird is pulling.

Another Student: It's like a hanger.

Teacher: What's happening?

Student: Like tug-of-war. (Varelas, 2014, p. 1258)

As this example in Varelas (2014) demonstrates, knowledge building in science learning is manifested in the constant movement between everyday language (e.g., "making a suctioning sound", "like a hanger") and scientific language (e.g., "worm anchoring itself in the ground with its bristles") through use of a variety of modalities. It is a process of what Bakhtin would describe as "appropriating authoritative discourse into internally persuasive discourse" (Hsu & Roth, 2014, p. 729). The language resources that students bring to the classroom become part of the language of science (Bernstein, 2000; Mortimer & Scott, 2003). Often science educators and science education researchers have viewed students' idiosyncratic expressions of their ideas, often verbalized through everyday language, as alternative conceptions—also called naïve conceptions or misconceptions— (Brown & Clement, 1989; Driver, 1981; Posner et al., 1982;

Treagust, 1988). Unlike this deficit perspective on students' language resources, a recent line of research adopts an asset-oriented approach highlighting the importance of integrating students' multiple linguistic resources and scientific language. Scholars in this vein argue that learning science requires making connections by shuttling between students' everyday languages and the language of science (Brown & Spang, 2008; Campbell et al., 2016, Maton, 2013, 2020). The main goal of these studies is to use students' everyday discourse as leverage to move to scientific discourse. However, fully integrating student epistemologies and language repertoires (rather than named languages such as home language or scientific language) in ways that co-construct the knowledge is uncommon (Bae et al., 2021).

Research has shown that science educators and researchers use everyday talk and science talk in their science teaching practices by using code-switching that focuses on shifts between two or more named languages—e.g., switching between English and Spanish or between home language and scientific language (Bae et al., 2021; Brown, 2021, Brown & Spang, 2008). However, examining how switching between named languages facilities shifts in meanings and how this switching transcends the boundaries of these languages through disciplinary practices (e.g., modeling practices), which foregrounds individual, emergent meaning-making resources for specific learning contexts rather than code-switching, has not yet been a focus of research in science education. This is one of the major unresolved issues related to the use of scientific discourse addressed in science education research (Bae et al., 2021). It is important to develop insights into context-specific practices that help students mesh a variety of language resources together to facilitate knowledge construction in science classrooms, which goes beyond code-switching (or double talk, as defined by Brown and Spang [2008]) as "superficial hooks" (Bae et al., 2021).

Constructing knowledge by crossing back and forth between everyday language, and the language of science is not an easy task for students to accomplish (Mortimer & Scott, 2003). One reason is that while students tend to use the embedded ways of thinking that manage their everyday world, they are required to move to the disembedded modes of thinking, which are abstract and symbolic, in learning science (Blown & Bryce, 2017). This shift between everyday thinking and scientific thinking is a progressive and iterative process, and students do not simply learn how to disembed their ways of thinking and speaking (Blown & Bryce, 2017). Consider the following example from Mortimer and Scott (2003). When we drop a ball, it falls to the ground. Why does the ball fall to the ground? With everyday ways of thinking about this scientific phenomenon and using language, we might argue that the ball falls because we let it go. With scientific ways of conceptualizing this phenomenon and using language, we argue that the ball falls because of gravity. Understanding the similarities and differences between these two statements and being able to draw on each as the context demands is important in science learning. This switch between embedded and disembedded ways of thinking along with the associated language use gives students opportunities to recontextualize their notions (Bernstein, 2000) and build knowledge by moving flexibly and confidently between everyday ideas and scientific ideas (Maton, 2013; Mortimer & Scott, 2003).

Why is moving between everyday language and scientific language important for knowledge building in science? Positioning knowledge-building practices at the center of learning and teaching, a sociological framework known as Legitimation Code Theory (LCT), in particular the dimension of semantics, proposes an answer to this question, and it argues that knowledge building requires both downshifting and upshifting between less condensed meanings and more condensed meanings (Maton, 2014b). Knowledge-building practices should include constantly packing and unpacking concepts by condensing meaning within symbols, phrases, gestures, and actions and relating scientific concepts to everyday examples (Maton, 2013). It means that learners should learn how to leverage their linguistic resources so that they can move flexibly between everyday language and scientific language to succeed in building knowledge in science classrooms.

Success in crossing between everyday language and scientific language, while building knowledge in science, is closely related to the types of discourse and modalities (ways of co-articulating knowledge through verbal, gestural, and pictorial modes) that are used within learning environments (Lemke, 2001; Norris & Phillips, 2003). An important reason for this connection is that the use of diverse modalities beyond scientific language allows learners to draw from meaning-making repertoires at their disposal (Grapin, 2019). These diverse modalities are considered epistemic tools that can be used to engage in disciplinary practices because they facilitate knowledge building by expanding channels through which diverse language resources are transacted (Grapin, 2019; Kelly & Cunningham, 2019). Conceptualizing scientific language as a unique hybrid, Lemke (2004) argued that learners should use a variety of modalities simultaneously to build knowledge while engaging in disciplinary practices in science classrooms.

Disciplinary practices should facilitate the use of multimodality in science instruction (National Research Council [NRC], 2012). One way of facilitating multimodal teaching and learning in science is by developing and using models, one of the eight science and engineering practices identified in the Next Generation Science Standards (NGSS) that established expectations for what K-12 science students should know and be able to do (NGSS, 2013). The practice of modeling relies heavily on multimodality because it involves using and orchestrating multiple resources that uniquely contribute to knowledge building in science learning (Pierson et al., 2021). However, research in science education has not paid enough attention to the multimodal aspect of modeling practices. Modeling forefronts multimodality while building knowledge in science because models and model development include different modes of representation such as physical materials, visuals, written and oral language, mathematical expressions, and gestures (Boulter & Buckley, 2000).

Since model construction involves the process of knowledge refinement by conjointly using a variety of modes of representation (Pierson et al., 2020), it provides a useful way to enhance the ways knowledge is produced and facilitates shifts between everyday language and scientific language. Students receive the greatest benefit from using multimodality in response to their needs, incorporating new modes into knowledge building (Kress et al., 2014). Another important argument in favor of multimodal modeling practices is that meaning emerges from the interlacing across a variety of representations within a multimodal system such as models (Kress et al., 2014).

While educational policy documents (e.g., American Association for the Advancement of Science [AAAS, 1993], Next Generation Science Standards [NGSS, 2013], National Research Council [NRC, 2000], Rutherford & Ahlgreen, 1990; Victor & Kellough, 2000) emphasize the importance of gaining experience with natural and social phenomena through scientific practices such as developing and using models, these documents do not highlight the multimodal aspect of these scientific practices. For instance, the recent science standards emphasize scientific inquiry practices as the cornerstone of science teaching and learning, and it neglects that science learning is also about using diverse language resources (NGSS, 2013). Research on modeling practices tends to be largely grounded in the European/Western scientific perspectives that value representational knowledge at the individual level (Schwarz et al., 2022). This approach focuses on the cognitive aspects of using modeling practices and underestimates the importance of incorporating diverse ways of knowing and communicating into modeling practices from a sociocultural perspective (Schwarz et al., 2022). There is limited research on modeling that focuses on the ways that the dynamic interaction of learners mediates their understanding of new constructs, informed by their lived experiences and their linguistic and cultural repertoires. Through such dynamic and ever-evolving interactions in modeling, learners engage in science practices in a meaningful way and succeed in a knowledge-building environment. For a successful science learning and teaching experience, considering the intersection between multimodality and science practices is key. Modeling practices open up science instruction for an explicit integration of multimodality into meaningful knowledge-building in science classrooms.

For students to experience the explicit integration of multimodality into meaning-making with modeling practices, teacher knowledge is of great importance in designing and implementing modeling-based science teaching practices as part of their teacher education program (Windschitl, Thompson, & Braaten, 2008). They need support in enhancing their knowledge of science teaching with models and modeling as part of their professional learning experience (Danusso, Testa, & Vicentini, 2010). Such experience should support both their learning about complex science ideas and their pedagogical content knowledge about how to facilitate student learning by using modeling practices (Crawford & Cullin, 2004; Zangori et al., 2017).

With limited experience teaching science with models and modeling, science teachers also encounter an additional challenge of implementing NGSS due to the change in student demographics in U.S. science classrooms (US Department of Education [USDED], 2019). Since the number of students with diverse linguistic, cultural, and racial backgrounds has been increasing in classrooms, science teachers need opportunities to enhance their knowledge and pedagogical skills in implementing modeling practices in ways parallel to educational reform efforts to meet the learning needs of their students (e.g., NGSS). Teachers should know how to facilitate rich meaning-making experiences that can emerge in modeling practices through the integration of diverse emergent semiotic resources into learning. They should also take advantage of language affordances of modeling practices which have not yet been a focus of science education research and practice. One way of accomplishing this goal is to provide both inservice and preservice teachers with opportunities to learn the same way students learn.

To respond to these issues, the overarching goal of this study was to expand current notions of what modeling can do for learners and how to engage learners in modeling practices. In doing so, as a multimodal scholar, I conceptualize modeling as a multimodal practice in which diverse languages and other semiotic resources are welcomed and encouraged in knowledge building. I refer to this practice of modeling as multimodal modeling to emphasize the idea that meaningful and rich meaning-making can be facilitated through modeling practices. Within this conceptualization, diverse modalities emerge from the interactions between learners, learning context, and learning materials (Kress et al., 2014). This social semiotic perspective differs from some models and modeling research that view language resources as stable tools, possessed by learners or provided by teachers (e.g., Baumfalk et al., 2018; Cheng & Brown, 2015; Dauer & Long, 2015; Miller & Kastens, 2018; Schwarz et al., 2009). There is limited research on modeling that focuses on the fluid, dynamic, and emergent nature of language in science learning. The exploration of emergent language resources in this study is expected to offer insights into the understanding of how they provide opportunities for learners to grapple with the complexity and technicality of scientific language (Brown, 2021). In addition, multimodal modeling practices using emergent language resources, in this study, are meant to promote horizontal (collaborative) knowledge-building experiences rather than vertical (hierarchical) ones in which background knowledge, experience, and language resources are passed from expert/teacher to non-expert/learner to generate a specific type of knowledge in classrooms (Doran et al., 2021). This approach to modeling practices was expected to encourage learners to use and generate diverse language resources while engaging in modeling practices to build knowledge, helping them overcome the barrier that technical scientific language can create in science learning.

One may ask, what is it about multimodality that makes knowledge building effective by facilitating the shift between everyday language and scientific language? How can we show that students are learning scientific ideas and concepts when they engage in multimodal modeling practices? Existing efforts to explain how multimodality helps students learn are useful but are not robust enough to explain student-constructed representations and the transformation among and the integration of modalities in building knowledge in science classrooms (Yore & Hand, 2010). Research on multimodality in science education has examined how students develop an understanding of science ideas by simultaneously using multiple modalities such as visuals, symbols, gestures, haptic experiences, and embodied actions (e.g., Hand et al., 2009; Jaipal, 2010; Prain & Waldrip, 2006; Tang & Moje, 2010). There has also been an emphasis on how re-representing the same idea using different modalities (e.g., graph to text to drawing) helps students learn (e.g., Ainsworth, 2008; Gilbert & Treagust, 2009; Tytler et al., 2020; Waldrip & Prain, 2012). There are limited instances of providing insights on how multimodality within the context of modeling practices helps students build knowledge. There have been many studies on developing and using models in science education, which consider models to be a single modality—either a diagram or written explanation (e.g., Baumfalk et al., 2018; Passmore & Svoboda, 2012). In this case, the purpose of modeling is to move from complex to simplified meanings by making abstract concepts concrete (e.g., Silva et al., 2013; Weinburgh et al., 2018). However, building a conceptual understanding of science relies on knowledge that emerges from the interlacing of various multimodalities to facilitate both packing and unpacking concepts, relating scientific concepts to everyday examples while also condensing meaning within abstract theoretical ideas (Kress et al., 2014; Maton, 2013). There are also some studies incorporating additional modalities into modeling practices such as the use of gestures along with explanatory models in science learning (e.g., Mathayas et al., 2021; Zohar & Levy, 2019). From this perspective, the additional modalities are seen as scaffolds rather than an important aspect of the model itself or the process of modeling. Research in science education has not focused on how to highlight and incorporate rich meaning-making through multimodality that emerges in modeling practices and what theoretical or analytical frameworks are available to study this.

This study expects that multimodal modeling practices have the potential to (a) enhance students' knowledge-building experience through constant shifts in meanings (i.e., packed vs. unpacked), (b) support switching between everyday language and scientific language to make science ideas accessible to all students, and (c) develop a better understanding of models and modeling in knowledge building in science. Using one of the dimensions of LCT, semantics (detailed in Chapter 2), as a theoretical and analytical framework, this study aimed to investigate how multimodal modeling practices can help learners build knowledge in science by leveraging their linguistic resources. To do so, this case study focused on the knowledge-building processes where a group of preservice elementary science teachers developed a model of how energy is transferred in glycolysis (the first step in cellular respiration), used the model to interact with a science text, and then reflected on their understanding of models and modeling in knowledge building.

To involve preservice elementary teachers in an exemplary situation of how rich meaning-making can emerge in modeling practices using multiple semiotic resources, the practice of modeling was implemented with preservice elementary teachers as if they were students in the context of this study (see Justi & van Driel (2005) for a similar implementation in which preservice teachers were positioned as students). The aim was to help students become sensitive to diverse ways of knowing and communicating and the importance of taking students' diverse semiotic resources into account in science learning with modeling practices. The involvement of preservice elementary science teachers in this study is crucial for two reasons. First, preservice elementary science teachers put themselves into the shoes of younger students and learn energy transfer in glycolysis by developing a model, which is unfamiliar to them (see Table 3 for their self-reported background both in cellular respiration and modeling practices). This experience provides them with an opportunity to see how one of the most challenging topics in life science can be learned engagingly through multimodal modeling practices. Based on my experience teaching preservice elementary teachers, I know that many student teachers lack science content knowledge, find scientific concepts intimidating, and do not identify as science persons. I expect to see that their participation in this study as learners engages them in science learning and brings out the science person in them.

Second, preservice elementary science teachers have a chance to enhance their pedagogical skills in teaching science with multimodal modeling practices and develop a better understanding of models and modeling in science learning. Many teachers lack the knowledge and skills required to facilitate modeling practices to support their students' science learning (Justi & Gilbert, 2002) and are reluctant to implement modeling practices in teaching. Based on my observations during a professional development (PD) institute on teaching biology with models and modeling that was executed as part of the project I worked on (and the post-PD survey results), I know that the most common barrier to implementation of a model-based lesson perceived or anticipated by participants is time. They think that planning and implementing a model-based lesson is time-consuming. The second most common barrier is concern about how students might respond to a novel approach to learning (e.g., becoming more active learners or feeling frustrated as they encounter a different approach to learning). In addition, preservice teachers may have naïve conceptions similar to those of young learners when it comes to their understanding of what models are and what models are for in science learning. Learners tend to think that models are copies of their referents and that they reflect reality or that they are smaller versions of real phenomena (Dogan & Abd-El-Khalick, 2008; Tasquier et al., 2016; Windschitl et al., 2018). The idea that models are copies of reality should come as no surprise because of insufficient guidance by the framework for K-12 science teaching and teacher education programs on how to implement model-based lessons (Fackler, in press). Through their participation in this study, preservice elementary science teachers are expected to enhance their pedagogical skills to plan and implement model-based lessons, develop a better understanding of models and modeling in knowledge building, and have a chance to divert their attention away from the idea that models are smaller versions of real things.

Purpose Statement and Research Questions

The purpose of this qualitative study was to examine how multimodal modeling practices could help learners, in this case, preservice elementary science teachers, to build knowledge as they engaged with a complex science topic by leveraging their linguistic resources. Because of my interest in exploring the meaning-making that emerged as a result of multimodal modeling, I chose to conceptualize and analyze the discourse through the lens of Legitimation Code Theory (LCT), an approach in the sociology of knowledge that has been highly useful in exploring classroom practices (Maton et al., 2021). I chose to integrate the constructs of multimodality, modeling, and LCT in the study because I felt these approaches would support a complex and systematic understanding of what emerged. The approach differs from what Yore and Hand (2010) noted as pedagogical practices that use multimodality in science education to simplify scientific language and make abstract concepts more concrete (unpacking). This reductionist approach (i.e., explaining scientific terms in everyday language and making abstract concepts concrete) may not guarantee success in developing a conceptual understanding of a natural phenomenon (Buxton et al., 2019).

Using the constructs of multimodality, modeling, and LCT, this study aims to show that the multimodal resources and activities around the practice of modeling support specific types of shifts in meaning (i.e., increasing and decreasing semantic density) by facilitating the process of making connections between conceptual ideas and even adding new complexity to terms, ideas, phrases, and expressions that come from students' familiar way of sense-making and lived experiences. There have been attempts to conceptualize and explain how students can use their familiar ways of sense-making including multimodal resources in science learning. For instance, Brown (2019) suggests the idea of encoding vs. decoding. While encoding refers to developing symbolic representations of ideas students already know, decoding means making sense of symbolic representations that are generated by someone else—e.g., textbooks, teachers, or scientists. He conceptualizes encoding and decoding in the context of teaching urban, African

American students and presents these concepts as tools for educators who are interested in implementing meaningful and equitable science instruction and assessment. On the other hand, the approach in this study is expected to promote a semantic shift in meaning through the process of both unpacking and packing, which is called a downward and upward shift respectively (Maton, 2013). Additionally, it has the potential to create semantic shifts in meanings while switching between scientific language and everyday language, which eventually goes beyond the boundaries between these two separate named languages by leading to one heterogeneous repertoire in knowledge building and making science accessible to all learners (Grapin, 2019; Maton, 2013; Wei, 2018). Therefore, in this study, I aimed to explore the pedagogical potential of multimodal modeling practices in helping teachers to develop expertise in using modeling to leverage their students' language resources. I also aimed to provide an understanding of the potential of modeling to support a range of functional language use so that the practice can be used to pack and unpack ideas and break down the barriers caused by scientific language in knowledge building. This is worth investigating because the number of students with different cultural and linguistic backgrounds in the nation's public schools is on the rise, and prospective science teachers should be prepared to respond to the needs of this diverse student population in science classrooms (Schwarz et al., 2021).

I present here the analytical questions guided by the key concept of semantic density, which I plugged into my data. The notion of semantic density opens up a wide range of possibilities to explore and describe how multimodal modeling practices can facilitate knowledge-building processes by encouraging learners to use their linguistic resources. Aligning with the assumptions of the LCT semantics, the research questions that guided this study were:

1. How did multimodal modeling practices facilitate packing and unpacking meanings in knowledge building in science?
2. In what ways did multimodal modeling practices play a role for learners in their switching between everyday language and scientific language in knowledge building in science?
3. How did multimodal modeling practices influence learners' understanding of models and modeling in knowledge building in science?

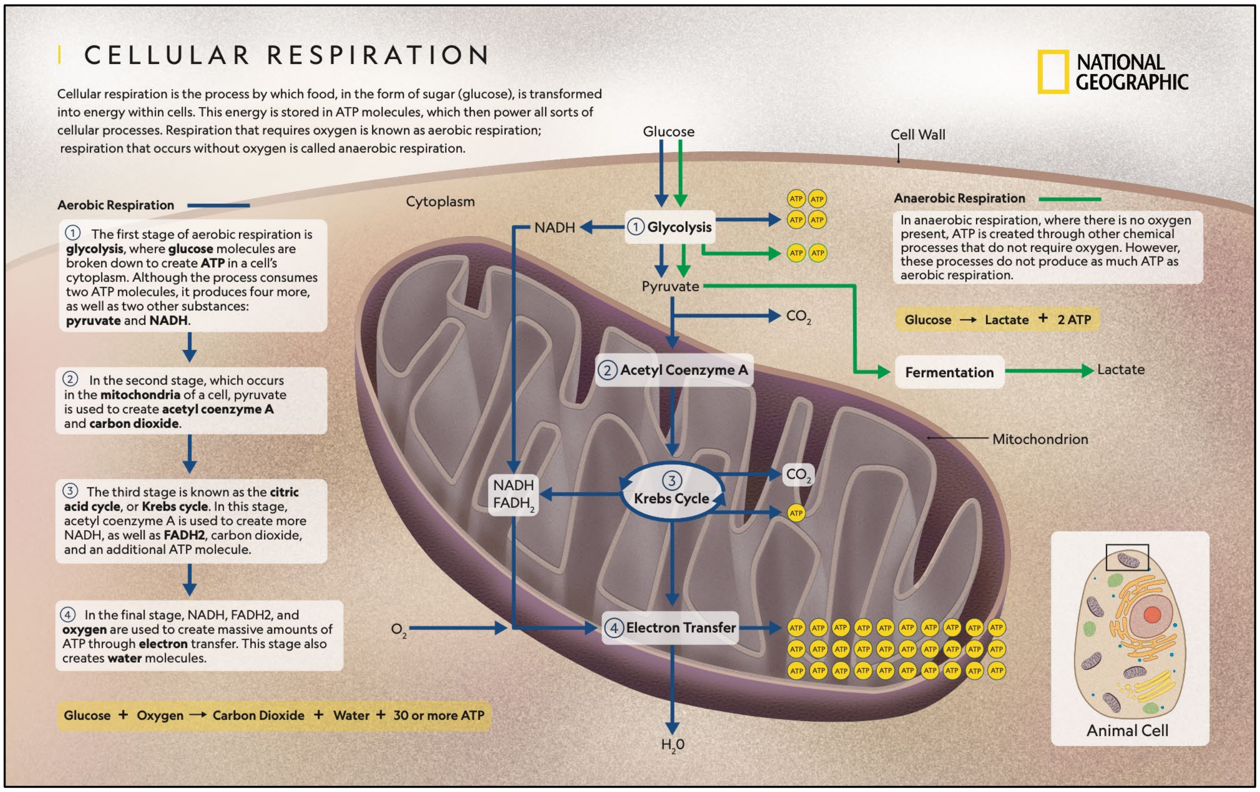
The research questions and the decision to examine the process of building knowledge through an LCT semantics lens are based on these three key considerations: (1) The condensation of meaning provides opportunities for packing and unpacking ideas in knowledge building. (2) The complexity and technicality of scientific language create a barrier to engaging in disciplinary practices. (3) The promotion of horizontal (collaborative) knowledge-building experiences through the use of diverse language resources expands notions of models and modeling in knowledge building.

First, the process of condensing meaning helps learners convey meaning in compact nominalizations and offers a greater degree of flexibility in packing and unpacking these meanings when needed in knowledge building (Conana et al., 2020; Halliday, 1998). Packed meanings and compact nominalizations are abstracted from immediate experiences to build generalizable new entities so that they can be functional and productive further in knowledge-building processes (Christie, 2001; Veel, 1997). Nominalizations are about re-meaning (Halliday, 1998). For instance, packed meaning can be used to establish cause-and-effect relationships between ideas and concepts or to organize previously stated information (Veel, 1997). This study examines how multimodal modeling practices promote the process of condensing meaning.

Second, scientific language itself is the biggest barrier to engaging in disciplinary practices in science classrooms (Lemke, 1990). Scientific language entails some unique challenges such as the informational density (complexity) and specialized content of science (technicality). When learners are not provided with opportunities to switch between everyday language and scientific language, they may end up feeling overwhelmed by the complexity and technicality of the scientific discourse. From the perspective of LCT semantics, learners also struggle to develop a conceptual understanding of scientific concepts when they lack opportunities to unpack these concepts by moving from technical, complex meanings to simpler, everyday meanings as well as pack these concepts by moving from simpler, everyday meanings to technical, complex meanings and relating them to other theoretical ideas (Buxton et al., 2019; Maton, 2013). Cellular respiration, for instance, is one of the most challenging topics in biology because the traditional cellular respiration storyline involves lengthy metabolic pathways and multiple unfamiliar terms and symbols (see Figure 1) to learn (White, 2016). Therefore, this study expects that multimodal modeling practices would offer a way to switch between the complex and technical language of science and everyday language while building knowledge about cellular respiration. Learners need to become the right kind of knower in science and develop fundamental scientific literacy skills such as comprehending or writing science texts (Norris & Phillips, 2003).

Figure 1

The Metabolic Pathways in Cellular Respiration, Adopted from Parks (2020)



CELLULAR RESPIRATION

Cellular respiration is the process by which food, in the form of sugar (glucose), is transformed into energy within cells. This energy is stored in ATP molecules, which then power all sorts of cellular processes. Respiration that requires oxygen is known as aerobic respiration; respiration that occurs without oxygen is called anaerobic respiration.

Aerobic Respiration

① The first stage of aerobic respiration is **glycolysis**, where **glucose** molecules are broken down to create **ATP** in a cell's cytoplasm. Although the process consumes two ATP molecules, it produces four more, as well as two other substances: **pyruvate** and **NADH**.

② In the second stage, which occurs in the **mitochondria** of a cell, pyruvate is used to create **acetyl coenzyme A** and **carbon dioxide**.

③ The third stage is known as the **citric acid cycle**, or **Krebs cycle**. In this stage, acetyl coenzyme A is used to create more NADH, as well as **FADH2**, carbon dioxide, and an additional ATP molecule.

④ In the final stage, NADH, FADH2, and **oxygen** are used to create massive amounts of ATP through **electron** transfer. This stage also creates **water** molecules.

Glucose + Oxygen → Carbon Dioxide + Water + 30 or more ATP

Anaerobic Respiration

In anaerobic respiration, where there is no oxygen present, ATP is created through other chemical processes that do not require oxygen. However, these processes do not produce as much ATP as aerobic respiration.

Glucose → Lactate + 2 ATP

Lastly, multimodal modeling practices, in this study, are conceptualized in such a way that promotes horizontal (collaborative) knowledge-building experiences rather than vertical ones as seen in traditional science teaching practices where knowledge and language resources are passed from expert/teacher to non-expert/learner (Doran et al., 2021). This approach to modeling practices is expected to encourage learners to use and generate diverse language resources while engaging in modeling practices and have agency in their knowledge-building experience, helping them expand their notions of models and modeling in knowledge building. Given the participants of this study, this study highlights the perspectives of preservice teachers on multimodal modeling practices and how these practices influence their understanding of models and modeling in knowledge building in science. It is well-documented that prospective teachers have difficulty understanding what models and modeling are, what they do for learners, and how to engage learners in this practice (Abd-El-Khalick & Lederman, 2000; Crawford & Cullin, 2004; Günther et al., 2019). Most teachers lack comprehensive knowledge and skills to build models to support their students' science learning (Justi & Gilbert, 2002). This study expects that preservice elementary teachers appreciate the affordances of multimodal modeling practices in learning and teaching complex scientific ideas by fully integrating students' diverse linguistic resources into disciplinary practices to make science ideas accessible and meaningful to them. These diverse linguistic resources emerge from the interactions between learners, learning context, and learning materials (Kress et al., 2014) rather than being stable tools, possessed by individuals (learners or teachers), or provided by teachers. It is imperative for preservice teachers to be aware of the use of modeling practices in encouraging learners to incorporate their ways of thinking about and expressing scientific ideas and to know that modeling is a multimodal practice and needs to integrate diverse modes of communication based on the needs of learners.

Rationale: The Need to Go Beyond Reductionist Teaching Practices in Science Education

The rationale for integrating multimodality, modeling, and LCT semantics is grounded in my effort to address and avoid reductive science literacy practices. Reductionist perspectives on the pedagogical effects of multimodality in learning have long dominated educational research and practice, particularly when it comes to teaching science to learners with different cultural and linguistic backgrounds (e.g., Weinburgh et al., 2019). Yore and Hand (2010) also noted that pedagogical practices using multimodality in science education focus mostly on reducing complexity and making abstract concepts more concrete (unpacking). However, conceptual understanding of science requires meaning to emerge from the interlacing across different modalities that facilitate both packing and unpacking the concepts, relating scientific concepts to everyday examples—i.e., unpacking, and condensing these unpacked meanings back within symbols, phrases, expressions, gestures, or actions—i.e., packing (Kress et al., 2014; Maton, 2013).

With the multimodal nature of new science standards (i.e., NGSS), students are expected to engage in disciplinary practices through multimodality to develop a conceptual understanding of science and other content areas. However, K-12 classrooms have been dominated by the traditional conceptualization of multimodality in instructional practices, which is called the weak version of multimodality (Grapin, 2019). The weak version of multimodality indicates that semiotic resources such as gestures and drawings are temporarily used to scaffold learning (e.g., explaining a scientific concept with everyday words or phrases) and are disregarded once students use the prioritized ways of knowing and communicating in classrooms (Gibbons, 2006; Grapin, 2019). The main purpose of utilizing these modalities in teaching is either reducing the complexity of ideas or reducing the demand for language skills in using privileged ways of knowing and communicating (Brown, 2021; Grapin, 2019; Lemke, 2004; Silva et al., 2013; Weinburgh et al., 2018).

One common practice among science teachers is using multiple modes to simplify scientific language and make it accessible to students by explaining technical terms and concepts using concrete examples from everyday life (Maton, 2013). For instance, in studies incorporating models and model development into science teaching, the purpose of developing and using models is to facilitate only one type of semantic shift in scientific discourse in classrooms: reducing the complexity of scientific concepts (e.g., Silva et al., 2013; Weinburgh et al., 2018; Wu et al., 2019). Multimodality can also help connect ideas conceptually and increase the complexity of everyday or scientific terms, ideas, phrases, and expressions rather than only reducing the complexity of ideas (Maton, 2013). As Solomon (1983) argued,

> The deepest levels of understanding are achieved neither in the abstract heights of pure physics, nor by a struggle to eliminate the inexact structures of social communication, but by the fluency and discrimination with which we learn to move between these two contrasting domains of knowledge [everyday vs. scientific]. (Solomon, 1983, p. 58)

"Using rich multimodal and linguistic repertories that they [students] already may use in their everyday lives but that are silenced in school contexts" can "disrupt reductive teaching" (Harman & Burke, 2020, p. 151).

In this vein, it is important to address the pedagogical potential of multimodal modeling practices in helping teachers gain knowledge and skills to support students in building knowledge by switching between scientific language and everyday language. Multimodal modeling practices should help learners build knowledge about scientific phenomena by providing them with an organizing structure to think with and an intermediate language to communicate scientific ideas. This is worth investigating because the number of students with different cultural and linguistic backgrounds in the nation's public schools is on the rise, and prospective science teachers should be prepared to respond to the needs of this diverse student population in science classrooms.

Linking LCT semantics to the modeling literature in a novel way, this study is the first attempt to illuminate how multimodal modeling practices can support epistemological and linguistic access to disciplinary knowledge-building practices in science education. Research that seeks to explore multimodality and modeling in relation to the learning science and the language generation functions of modeling practices remains under-theorized. To this end, Chapter 2 presents a targeted review of the literature on learning with models and modeling in science education and learning through multimodality in science education. This chapter concludes with my positionality statement and the definitions of key terms used in this study.

Positionality Statement

This positionality statement is not fixed or static. As an educator and researcher, I am constantly evolving in my understanding of myself and the world around me.

I am writing about my positionality in this study because "a researcher's background and position will affect what they choose to investigate, the angle of investigation, the methods judged most adequate for this purpose, the findings considered most appropriate, and the framing and communication of conclusions" (Malterud, 2001, pp. 483-484). There is no neutral research (Halse & Honey, 2005). In this study, I was surrounded by the following: the data, the theory, my memories of the interview process, my roles as a researcher and an instructor, my experience working on an NSF-funded modeling project, my interactions with the participants, my current engagement with qualitative research through interpretive and constructivist approaches to and interdisciplinary frameworks in science education research, my own personal and professional knowledge of being a recent immigrant and bilingual speaker in the United States, my being a first-generation graduate student, my being an international scholar, my being a science person, my being a teacher, and my being a mother. All this awareness, assemblage, is about how the different aspects of this study constitute or make one another. In what follows, I explain my perspectives on learning and research, reflect on the relationship between me and the participants, and describe my interactions with the topic of my study.

Adopting a sociocultural perspective, I believe learning is viewed as a process of internalization that requires the reorganization and reconstruction of knowledge. The process of learning is active in three ways: learners should be active, educators should be active, and the learning environment in which learners can socially build knowledge should be active (Davydov, 1995). Learning occurs through the interactions between learners, practices, and learning settings (Lave, 1988). Social interactions in the classroom cultural context influence knowledge-building practices (Lave & Wenger, 1991; Lemke, 2001; Vygotsky, 1978). Thus, individuals working in a group may develop different understandings because they incorporate their cultural perspectives (e.g., home culture, language, or dialects) into meaning-making processes (O'Loughlin, 1992). As a constructivist researcher, I believe there are multiple realities that are socially and experientially based, local, and specific; multiple knowledge can coexist; background assumptions and values are ineluctable in shaping inquiry outcomes. As a multimodal scholar, I also believe that a language (not a specific named language system or structure) in general emerges through interactions in specific contexts to develop a shared understanding. It is "emergent, not fixed, in flux rather than static" (van Lier, 2004, p. 87). It is a multi-semiotic, multisensory, and multimodal resource for knowledge building.

The relationship between me, the researcher, and the participants was fluid, not one-sided. Each one of us was constantly influencing the other through our interactions. I collected my data in my first semester of teaching undergraduate students and in my first experience teaching during a global pandemic. Most of the participants had experienced only online classes since March 2020 and were very interested in my in-person class in the spring semester of 2021 when I collected my data. The resumption of in-person classes increased their motivation to learn through modeling, which is a hands-on and fun practice, in a face-to-face context. Witnessing their motivation to learn, I was very confident about my teaching and the quality of the data I collected for my project. At the end of the lesson, I even received a lot of interesting questions from learners (student teachers) about this lesson and my research project. On the other hand, a few student teachers requested an online version of the lesson due to their concerns about Covid-19. To be honest, I did not expect to teach this lesson in a hybrid online format. These student teachers participated in my class via Zoom on the day I collected my data. I shared the digital copies of the learning materials (except the physical manipulatives) and instructed them through Zoom while I was present in class. From time to time, I felt nervous because I was not sure if the Zoom environment was conducive to learning with the type of modeling preservice teachers engaged in. This could have affected my teaching performance and the interest of the online student teachers in participating in interviews and other parts of the data collection.

I have also had personal experience with the topic of my study. During my doctoral program, I was hired to work as a graduate research assistant for an NSF-funded project. This experience presented me with several opportunities. First, the project team and I invested a great amount of time in developing (and even producing from scratch) physical manipulatives to make abstract energy-carrying molecules concrete and to present the concept of transfer of energy to high school students in an accessible way. Second, we developed a five-day model-based unit including student and teacher worksheets, PowerPoint lecture notes, animation, informational texts, reading material, wrap-up activities, formative assessments, and summative assessments. I was involved in every single part of the development of this unit. Third, in the summer of 2018, we had a professional development institute for inservice science teachers from Alabama and Georgia. Teachers were provided with instructional materials we developed and learned how to use models and modeling to teach cellular respiration. We, as researchers, had a chance to receive feedback from teachers on the modeling lesson that we developed for this project. I had a chance to observe how inservice teachers engaged in the model-based lesson and with the learning materials we developed. Moreover, by embedding myself in this research project on modeling and collecting and analyzing data, I was able to see and talk about how effective the modeling lesson was.

I know that my positionality not only shapes my research but influences my interpretation, understanding, and ultimately my belief in the truthfulness of others' research that I have read or been exposed to (Holmes, 2014). This open and honest disclosure of my positionality shows where and how I believe that I have influenced my research. The reader is welcome to make an informed judgment as to my influence on the research process and how truthful they feel my research is.

Definitions of Key Terms

Academic Language: The language used in schools to learn, speak, and write about academic subjects (Valdés et al., 2005)

ATP (Adenosine triphosphate): A chemical found in most living cells used for energy

Cellular Respiration: The metabolic process by which food, in the form of sugar (glucose), is transformed into energy within cells

Glucose: A type of sugar obtained from foods and used for energy

Glycolysis: Breakdown of a carbohydrate (such as glucose) using enzymes, resulting in the release of energy

Everyday Language: Language used by students or teachers to do disciplinary work in classrooms (Bunch & Martin, 2021)

Knowledge Building: Collaborative discursive efforts intended to continually conceptualize, enhance, and refine ideas (Bereiter, 2002; Scardamalia et al., 2012)

Legitimation Code Theory (LCT): A sociological and practical theory that integrates ideas from across a variety of disciplines such as sociology, systemic functional linguistics (SFL), and literature (Maton, 2014a; Ramírez, 2018). LCT has been widely used by researchers alongside concepts from the framework of SFL that Yore and Hand (2010) listed among the promising sources for developing a theoretical foundation to explain how multimodality facilitates learning and teaching in science.

Modality: "A cluster of modes that together function to make meaning" (Harman et al., 2022, p. 305)

Mode: "A channel of communication that is culturally ratified as a meaning-making set of signs such as gesturing and talking" (Harman et al., 2022, p. 305)

Model: Simplified representations of natural phenomena (Lehrer & Schauble, 2006)

Modeling: An epistemic process of constructing, evaluating, revising data, evidence, claims, and reasoning with models (Lehrer & Schauble, 2006)

Multimodality: Communicating through "gestures, facial expressions, images, equations, maps, symbols, diagrams, charts, videos, graphs, computer-mediated content in addition to the use of spoken and written language" (WIDA, 2020, p. 19)

NADH (Nicotinamide adenine dinucleotide): A coenzyme found in all living cells that acts as an energy carrier, transferring electrons from one reaction to another

Packing: Condensing meanings or going from simpler meanings to more condensed, complex, or technical meanings (Clarence & van Heerden, 2021)

Scientific Language: “Disciplinary language that is derived from written texts by professional scholars or textbook writers” (Bunch & Martin, 2021, p. 542)

Semantic Density: The relative complexity of meanings and condensation of meanings within a concept or specialized term (Clarence & van Heerden, 2021)

Semantics: One of the dimensions of LCT that considers social fields of practice as semantic structures whose organizing principles are conceptualized as semantic codes, centering around strengths of semantic gravity and semantic density (Maton, 2013)

Underlying Structures: Constructed references across multiple representations or scenarios of content to be learned (Opfermann, Schmeck, & Fisher, 2017)

Unpacking: Moving from condensed, complex, or technical meanings to simpler and contextualized meanings (Clarence & van Heerden, 2021)

CHAPTER 2

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

In this chapter, I present a targeted literature review in two sub-sections: learning with models and modeling and learning through multimodality in science education. In the first sub-section, I discuss how the science education literature talks about models and modeling and how the relevant studies inform my conceptualization of models and modeling for this study. In the second sub-section, I present research findings on the pedagogical effects of multimodality in the science education literature and theoretical or analytical frameworks that are used to explain how knowledge building occurs through multimodality in science learning and teaching and discuss research on multimodality within the context of scientific practices. The chapter concludes with the theoretical framework of the study, Legitimation Code Theory–semantics.

Learning with Models and Modeling

This section brings the literature together to portray how models and modeling practices are viewed and how science learning with models and modeling is conceptualized in the field of science education. Using this literature, I present how science learning with models and modeling is conceptualized in this study.

What are Models and Modeling Practices? How is Science Learning with Models Conceptualized?

National science education reform in the United States has advanced developing and using models as one of eight scientific practices that all science learners should demonstrate proficiency with by the end of the 12th grade (NGSS Lead States, 2013; NRC, 2012). The

Framework for K-12 Science Education describes two types of models, mental models, and conceptual models. Mental models are incomplete, unstable, and personal representations that reflect learners' beliefs about a system or phenomenon (Johnson-Laird, 1983; Norman, 1983; Tytler & Prain, 2010). Conceptual models, the topic of this study, are constructed in scientific discourse by piecing together relevant information to explain a phenomenon (Nersessian, 1995). They can be thought of as simplified representations of scientific phenomena, objects, events, or ideas (NRC, 2012; Schwarz et al., 2009).

While models are simplified representations of natural phenomena, modeling can be described as the epistemic process of constructing, evaluating, revising, and reasoning with models (Lehrer & Schauble, 2006). Similarly, Hestenes (1996) describes modeling as a cognitive process whose "primary purpose is the making and using of conceptual models" (Hestenes, 1996, p. 35). Hestenes (1993) argues that "since modeling is the 'name of the game' in science and technology, it should be the central theme of science education" (Hestenes, 1993, p. 1).

Models and modeling have been defined in many ways in science education. Given the plurality of both the meaning of models and the process of modeling, it is difficult to define the terms model and modeling ontologically (Mahr, 2011). In response to this challenge, Mahr (2011) suggests asking what qualifies something as a model. The answer to this question affects how we conceptualize models and the process of developing models and how we make judgments about the nature and functions of a model (Günther et al., 2019). Discussing a similar issue, Passmore et al. (2014) argue that our focus should be on sense-making through models rather than on a model of something as an end in itself.

Hesse (1966) argued that "conceptual models are strongly predictive since they give new interpretations of theoretical terms into observables which are non-arbitrary in the sense that they are determined by the model itself" (Hesse, 1966, p. 89). In this paper, unless explicitly stated otherwise the term models refers to conceptual models. In examining the literature on models and modeling, I am not concerned with identifying and describing the form of students' representations (e.g., whether they are images, explanations, drawings, or computer simulations). Rather, I am interested in the meaning that is represented through models and modeling.

There are also many ways of thinking about the characteristics and functions of models. Models can function as a means of (deliberate) simplification (Michaels et al., 2008; Schwarz et al., 2009); a medium to present and explain scientific data (Bailer-Jones, 2003; Krell et al., 2015); an example of a general schema (Gilbert & Justi, 2016); or a mediator between scientific laws or theories (Morrison & Morgan, 1999). In addition, models can function as a research tool to make predictions (Windschitl et al., 2018); an object to gain new insights (Odenbaugh, 2005; Passmore et al., 2014; Krell et al., 2012); or an epistemic tool, i.e., drawing inferences and reason through building models and manipulating them (Krell et al., 2012).

Related to the characteristics and functions of models, two of the learning goals listed in the Framework for K-12 Science Education encourage students to engage in modeling activities in school science (NRC, 2012, p. 58):

> 1. Constructing drawings or diagrams as representations of events or systems—for example, draw a picture of an insect with labeled features, represent what happens to the water in a puddle as it is warmed by the sun, or represent a simple physical model of a real-world object and use it as the basis of an explanation or to make predictions about how the system will behave in specified circumstances.

2. Representing and explaining phenomena with multiple types of models—for example, representing molecules with 3-D models or with bond diagrams—and moving flexibly between model types when different ones are most useful for different purposes.

These goals listed in the Framework highlight the importance of students developing and using models to represent, explain, and predict scientific phenomena. These important aspects of models and modeling in teaching and learning have also been emphasized by a large body of research on models and modeling in the context of both teachers and teaching (e.g., Brewe, 2008; Crawford & Cullin, 2004; Daly & Bryan, 2010; Danusso et al., 2010; Günther et al., 2019; Justi & Gilbert, 2005; Justi & van Driel, 2005; Miller & Kastens, 2018; Schwartz & Skjold, 2012; Schwarz et al., 2009) and students and learning (e.g., Baumfalk et al., 2018; Brown & Clement, 1989; Cheng & Brown, 2015; Krell et al., 2015; Mulder et al., 2016; Pierson & Clark, 2018; Samarapungavan et al., 2017; Zangori et al. 2017). In addition to these empirical studies, there are some critical and detailed reviews and syntheses of the literature on the nature of models and modeling and their uses in science teaching and learning (e.g., Chamizo, 2013; Oh & Oh, 2011). Empirical research on learning with models and modeling has conceptualized models as representations of natural phenomena, and they are tools to describe, explain, predict (hypothesize), and communicate scientific concepts (Chamizo, 2013; Oh & Oh, 2011). Based on this observation, it is true to say that the explanatory and predictive power of models and modeling is the most common focus of the studies on learning and teaching through models and modeling in science.

Alongside the typologies of models, their functions, and relevant learning goals for science learners, the literature on models and modeling in science education has provided a fruitful discussion on how learners view models vs. how they should think about them. The literature extensively discusses learners' tendency to think that models are copies of their referents, i.e., that they reflect reality (Capps & Shemwell, 2020; Dogan & Abd-El-Khalick, 2008; Grosslight et al. 1991; Harrison & Treagust, 1996; Ingham & Gilbert, 1991; Tasquier et al., 2016; van Driel & Verloop, 1999; Windschitl et al., 2018). When students consider developing models as a representational task, they are more likely to create replicas by focusing on explicit features (material aspects) instead of conceptual features (structural aspects) of the phenomenon. This distinction between the material aspect and structural aspect (form vs. function) situates models in the context of their use. This is not to say, however, that models represent only structural aspects of a phenomenon. Rather, as many scholars have proposed (e.g., Schwarz et al., 2009), I am suggesting that models should explain how a system itself works, not its arbitrary character (e.g., pendulum and harmonic motion).

As noted earlier, models are abstract (Gilbert & Justi, 2016; Gobert & Buckley, 2000), partial renderings that differ widely in their ways of representing scientific phenomena (Morrison & Morgan, 1999). Because of this, all models leave out certain details and information in their representation of a concept or system. The ways a model is developed may offer (more or less) abstract characterizations of a phenomenon.

All models are incomplete and inadequate to represent all aspects of a system, but they are still models of a particular system (Johnson-Laird, 1983; Passmore et al., 2014). This is not a deficiency because models are used to generate scientific explanations relevant to the specific aspect of a phenomenon (Nersessian, 1995; Schwarz et al., 2009). Models are tools for surrogate (or simulative) reasoning (Koponen & Tala, 2014; Swoyer, 1991). Scientific inquiry is carried out on models rather than on reality itself because important features of a system can be discovered through models (Swoyer, 1991).

When it comes to learning with models, psychology- and cognitive science-oriented viewpoints about models have dominated science education research. As the leading researchers in this area, Gentner (1983), Gick and Holyoak (1980), and Johnson-Laird (1983) focused on learning with conceptual models and the use of analogies in scientific reasoning. An analogy is a comparison that facilitates the mapping of systematic relations (Gentner, 1983). A good analogy uncovers common structures and helps learners draw further inferences (Gentner & Smith, 2013). Providing analogical bridges between unfamiliar ideas and knowledge that students already possess is an effective way to help students understand difficult scientific phenomena (Treagust et al., 1998). Learning through analogies has an important place in people's everyday learning and sense-making (Holyoak & Thagard, 1997).

Drawing on the theory of analogical learning (Gentner, 1983; Gick & Holyoak, 1980; Johnson-Laird, 1983), Nersessian (1995) highlighted the importance of analogical learning in using and developing models to understand the mechanisms behind the key features of scientific phenomena. Analogical learning entails "examples (as few as two) that are not particularly similar in semantic and perceptual features" (Holyoak & Lee, 2017, p. 459). Analogical learning explains how learners can formulate abstractions by seeking the common structure within scenarios that are similar in essence, but different on the surface (Catrambone & Holyoak, 1989; Gick & Holyoak, 1980). This means that individual components in the multiple scenarios might be semantically quite different, but the structural relations between those components are similar across the scenarios. Analogical thinking should help learners abstract and map correspondences between multiple scenarios and apply them to a new domain (target) by using select ideas. Because analogies involve rich relations (the complexity of the relations), abstraction ranges from low to high depending on the use of superficial similarities or key structural (relational) similarities over multiple examples (Holyoak et al., 2010).

Structural similarities are important in developing a complete understanding of scientific ideas and concepts. When it comes to learning about scientific concepts, students usually focus on the surface features of multiple instances of a phenomenon instead of seeking the underlying structures that define the phenomenon across instances (Goldstone & Son, 2005). In learning science, students should learn the underlying structure of scientific phenomena (Schwartz et al., 2011). Learning through analogies is one way of facilitating learning about the underlying structure of phenomena because analogies are all about figuring out resemblances between things that are different (Mitchell, 1993). Additionally, the process of identifying similarities and differences between two or more scenarios helps capture abstract structures and uncover underlying structural similarities across the cases (Gentner, 1983; Gick & Holyoak, 1983; Loewenstein et al., 2003).

Several studies have shown that analogical learning is effective in promoting scientific explanations and explaining mechanisms behind natural phenomena by providing students with an underlying structure that is abstracted from multiple scenarios (e.g., Guy et al., 2013; James & Scharmann, 2007; Vosniadou & Schommer, 1988; Yanowitz, 2001). For instance, students who were provided with a power plant analogy as they learned about mitochondria were more accurate in answering questions that required mechanistic explanations—such as, “What would happen if the shape of the enzyme changed?”—relative to those who learned without an analogy (Yanowitz, 2001). Moreover, this approach has promoted transfer in mathematics (Rittle-Johnson & Star, 2009) and science (Kuo & Wieman, 2015). Gick and Holyoak (1980) found that participants who abstracted the underlying structures from multiple scenarios were more apt to transfer them to novel situations than those who learned the scenarios without support for abstracting. Gick and Holyoak (1983) also found that if learners do not make sense of the underlying structure of the phenomenon, they are less likely to exhibit transfer to problem isomorphs, multiple instances that explain the same scientific idea, with different surface features.

Learning with Models and Modeling Practices in This Study

In what follows, I explain my conceptualization of models and modeling, which shares many characteristics with the literature discussed earlier. The modeling approach I use in this study follows Capps and Shemwell's (2020) synthesis modeling. Synthesis modeling is described as seeking the underlying structure from two scenarios that contain it. In this type of modeling, abstraction and analogous scenarios (two or more) play a central role. When developing a model through synthesis modeling, students are asked to work from two or more instances of a phenomenon that share an underlying structure but differ on the surface and abstract the structural similarities embedded in those instances.

Synthesis modeling is guided by the theory of analogical learning (Gentner, 1983; Gick & Holyoak, 1980; Johnson-Laird, 1983) explained earlier. An analogy can improve knowledge through abstraction—extraction of the common relational structure by drawing on similarities between multiple exemplars (Gentner & Smith, 2013). The analogy is an "inductive mechanism" and is "fallible" (Holyoak & Lee, 2017, p. 460), which fits the idea that models are incomplete and imperfect. However, using analogies and models in science education can still facilitate the understanding of key causal relations.

Induction is one of the philosophical foundations for the use of analogies (Bartha, 2013). Induction "uses observations to arrive at premises as well as relations between premises, which are then used to arrive at conclusions" (Nunes, 2012, p. 2066). Most explanations in the sciences, in particular biology and medicine, entail inductive processes (Schaffner, 1994). Using inductive processes is an important approach to developing scientific explanations of natural phenomena (e.g., Kuo & Wieman, 2016; Yanowitz, 2001). Similarly, learning the underlying structure of a mechanism, system, or event requires an inductive process in which learners conjointly observe multiple cases of a phenomenon and abstract the structural similarities (Gentner, 1983; Gick & Holyoak, 1983). This inductive approach to model construction, namely synthesis modeling, supports learners in abstracting that stable structure by simultaneously observing multiple sources of the phenomenon of interest (Capps & Shemwell, 2020).

Learning Through Multimodality in Science Education

This section first presents literature on multimodality in science education in general and then focuses on multimodality within the context of scientific practices, in particular using and developing models.

Multimodality in Learning and Teaching Science

Using multimodality in science learning environments is not new. Research findings on its pedagogical effects can be found in the science education literature dating as far back as the Progressive Era in education in the United States, when educators were encouraged to provide their students with different modalities in learning and teaching (Heiss, 1938; Reese, 2001). Studies have focused on how students build scientific understanding by simultaneously using a range of modalities such as visuals, symbols, gestures, haptic experiences, and embodied actions (e.g., Airey & Linder, 2009; Hand et al., 2009; Harman & Burke, 2020; Jaipal, 2010; Kress et al., 2014; Lemke, 1998; Prain & Waldrip, 2006; Rahm, 2004; Tang & Moje, 2010, Tang et al., 2011; Waldrip et al., 2010). There has also been an emphasis on how re-representing the same phenomenon using different modalities (e.g., graph to text to drawing) affects student learning (e.g., Ainsworth, 2006, 2008; Gilbert, 2005; Gilbert & Treagust, 2009; Kozma, 2003; Tytler et al., 2020; Van der Meij & de Jong, 2006; Waldrip & Prain, 2006, 2012).

In science education, Yore and Hand (2010) provided an overview of how multimodality has been taken up in science teaching and learning practices. They suggested that the ways of communicating science ideas should be multimodal and involve a variety of forms of modalities to facilitate both the understanding of and a fundamental literacy in science. The central question they raised in their review was how students engage in learning science with multimodality and how they use multimodality to generate knowledge. Regarding this question, they advocated linking perspectives and ideas from various disciplines—including cognitive psychology, linguistics, visual representations, models, model development, and systemic functional linguistics—to develop a coherent theoretical foundation for understanding how multimodality helps students build scientific knowledge.

Since Yore and Hand's (2010) thorough coverage of the earlier literature on this topic, there have been a few studies that have developed or used a coherent theoretical or analytical framework that can explain how knowledge building occurs through multimodality in science learning and teaching. Addressing the need for investigation of the use and theoretical justification of student-constructed representations (i.e., drawings) to learn science, Prain and Tytler (2012) presented a framework that integrates three dimensions to explain how and why representational construction supports learning in science. The framework, called representational construction affordances (RCA), included a semiotic dimension that involved the use of key features of symbolic and material tools to make meaning. It also discussed an epistemic dimension in terms of how student-constructed representations related to the broader picture of knowledge-building practices. Finally, it included an epistemological dimension in terms of how students can know through engaging in the challenge of representing causal accounts (reasoning) through semiotic tools (Prain & Tytler, 2012). With this framework, they examined a lesson and identified what they termed as an ‘enabling constraint’ as a key feature of each modal representation that was used to explain the same concept of evaporation. For instance, they found that the modality of role-play activities through embodied actions neglected to present molecular size but focused attention on spacing and movement. The findings emphasized what students learned rather than how they learned. Even though the framework is very promising in terms of focusing on knowledge building through multiple representations through three dimensions explained earlier, it does not explicitly theorize what makes different representations useful for knowledge building and how students build understanding within or across these representations.

In another study, Tang et al. (2014) explicitly addressed Yore and Hand’s (2010) call and proposed an integrative framework to investigate how students construct meaning with a variety of modalities. This framework draws on several theoretical concepts. To examine the transformation of one representation to another one, it draws on the theoretical notion of re-representation (Hubber et al. 2010) and transformative sign-making (Kress et al. 2014). To focus on the integration of multiple modalities and its multiplying meaning effect (Lemke 1998), the framework adapts the notion of semiotic affordances from systemic functional linguistics (Kress et al. 2014). Their framework entailed two dimensions, timescale, and compositional grain size, to illuminate student learning with multiple modalities. While timescale refers to the time students spend on one or more representations, compositional grain size is about “the elements that make up a representation” (Tang et al., 2014, p. 307).

> For example, the finest-grained components of a molecular depiction of air exerting pressure on its container are the lines (representing the container), dots (representing molecules), and arrows (representing motion) drawn in the diagram. . .the largest compositional grain size can be one or more diagrams in their entirety. (Tang et al., 2014, p. 307)

The framework examines student learning with multimodality at two levels (Tang et al., 2014): First, it focuses on the transformation of one representation to another (e.g., graph to text to diagram) and how one representation relates to others. This level entails a longer timescale and larger compositional grain size. Second, the framework explores semiotic affordances (meaning generated across modalities), including a shorter time scale and finer grain size. In their study, the researchers concluded that students' explanations of the phenomenon under study depended on the representation they focused on and interacted with. However, the framework developed and used by Tang et al. (2014), falls short of showing how students build knowledge and develop meaning through multiple modalities or what kind of knowledge students build through multimodality.

Using the same framework, Tang and colleagues (2016) examined how students' multimodal integration competency can be developed through explicit teaching of disciplinary literacy in science classrooms. In two, 1-hour physics lessons on the topic of waves, the researchers asked students to describe the movement of particles and the transfer of energy in transverse wave motion by talking, writing, and drawing. As an important contribution, this study provided insights on how to design and carry out multimodal learning activities that focus on developing disciplinary literacy and competency in using multimodality. The researchers did not address how the integration of different modalities supports students in learning science ideas.

Multimodality Within the Context of Scientific Practices

There is a well-established literature on multimodality embedded in science writing and argumentation practices in high school physics (e.g., Gunel et al., 2006, Gunel et al., 2016), chemistry (e.g., McDermott & Hand, 2012), and middle and high school science (e.g., Tolppanen et al., 2016) classrooms. There are some studies incorporating a single modality into modeling practices such as the use of gestures along with explanatory models in science learning (e.g., Mathayas et al., 2021; Zohar & Levy, 2019). However, little is known about how multiple modalities can be facilitated within modeling practices and what theoretical or analytical frameworks are available to study this. Using epistemic frames (justification, explanation, representation, identification of questions, data gathering, and evaluation of results) as an analytical framework, Campbell & Fazio (2020) examined the types and organization of practices in a science classroom in which a modeling-based learning unit was implemented to understand what sense-making practices were used, and how these practices supported student understanding. The study findings highlighted that verbal representations and diagrammatic models functioned as mediational tools to facilitate scientific practices such as asking questions about the phenomenon under study. The focus was on learning and using scientific practices rather than learning through multimodality modeling practices.

In the broader modeling literature, there are limited instances of providing insights on how multimodality within the context of modeling helps students build scientific knowledge. There have been many studies on developing and using models in science education, which consider models to be a single modality, such as a diagram (Baumfalk et al., 2018; Dauer &

Long, 2015), an illustration or drawing (Schwarz et al., 2009), a visual (Cheng & Brown, 2015), a three-dimensional physical representation (Miller & Kastens, 2018), and a verbal or written explanation (Passmore & Svoboda, 2012). From this perspective, as I discussed earlier, the purpose of modeling remains at the level of facilitating only one type of shift in scientific discourse in classrooms: moving from complex to simplified meaning (e.g., Silva et al., 2013; Weinburgh et al., 2018). Therefore, pedagogical practices using modeling focus primarily on reducing complexity and making abstract concepts concrete (unpacking). However, building a conceptual understanding of science relies on knowledge that emerges from the interlacing of various multimodalities to facilitate both packing and unpacking concepts, relating scientific concepts to everyday examples while also condensing meaning within abstract theoretical ideas (Kress et al., 2014; Maton, 2013).

Several studies showed that when modeling practices are coupled with or supported by multiple modalities and language resources such as drawings, verbal representations, visualizations, physical models, diagrams, gestures, and home languages, students better explain scientific ideas (Zohar & Levy, 2019), generate scientific knowledge (Acher et al., 2007), make sense of real-world phenomena (Campbell & Fazio, 2020), and develop a conceptual understanding of science ideas (Karlsson et al., 2019; Licona & Kelly, 2020; Pierson et al., 2020). Some studies also focus on multiple models in which the same or similar ideas are represented through multiple representations such as diagrams, physical models, computational models, and embodied models (Ke et al. 2021; Pierson et al., 2021). This is different from what I focus on in this study: multimodal models and modeling. In this study, I aim to show how a model itself (modeling product) and the model construction (modeling process) can be multimodal and convey multiple ideas and meanings.

In this study, I seek to show how meaning can be afforded and multiplied by multimodality and how multimodality facilitates knowledge building and shifts in classroom discourse. Models (as a product) and modeling (as a process) within the context of this study incorporate multimodality into knowledge-building practices in learning science ideas. Because different modalities lead to different meanings, these meanings can be intertwined across a variety of representations (embodied actions, symbols, or drawings) within a multimodal system such as models (Kress et al., 2014). Different modalities help students extend and enrich meaning developed through their experiences in modeling (e.g., using embodied actions to further elaborate on the ideas about how molecules get, have, and release energy; see Figure 5). Moreover, multimodal modeling practices have the potential to cross the gap in instruction (i.e., always facilitating downward shifts but not upward shifts) defined by Maton (2013). The process of multimodal modeling allows learners to meaningfully pack and unpack ideas using diverse language resources in knowledge building. Additionally, the multimodal aspect of modeling promotes flexibility in switching between everyday language and scientific language (Mortimer & Scott, 2003). This transition should not be considered a one-way process, because moving from scientific language to everyday language is not always helpful for promoting knowledge building, so students also need to move from everyday language to scientific language in knowledge building (Maton, 2013; Mortimer & Scott, 2003).

Based on the insights gained from this targeted literature review, research on modeling practices has widely emphasized abstract representational knowledge, individual learning processes and outcomes, and cognitive aspect of student learning while overlooking the potential of these practices to promote meaningful science learning by allowing learners to bring their diverse ways of knowing, lived experiences, and cultural and linguistic resources to learning environments. Research on multimodality in science education has focused on what students learn (rather than how students learn) through multimodality and how students transform and relate one modality to another. Some studies also discussed how educators should design and carry out multimodal learning activities, how multimodality facilitates scientific practices, in particular asking questions and defining problems, and how models can be utilized as one type of modality (rather than a combination of multiple modalities). These functions and purposes of modeling and multimodality seem to serve to facilitate procedural exercises in which learners are explicitly directed to use the practice of modeling and multimodality to accomplish a particular learning goal or curriculum development goal set up for them. Modeling practices and multimodality should be used in service of learners and their needs, and both should incorporate epistemological considerations of science and knowledge production (Ke & Schwarz, 2019).

Theoretical Framework

This study adopts Legitimation Code Theory (LCT) as a theoretical and analytical perspective on language that has been fundamental to exploring how knowledge building occurs in a social context. Yore and Hand (2010) listed the systemic functional linguistics, which LCT draws on (Maton et al., 2021), among the promising sources for developing a theoretical foundation to explain how multimodality facilitates learning and teaching in science. A line of recent science education research has recognized different perspectives that are provided by LCT to inform science teaching and learning practices (e.g., Georgiou, 2014; Kinchin et al., 2019; Lee & Wan, 2022; Maton et al., 2021). LCT has been used as both an analytical and a theoretical framework in science education and teacher education research (see Georgiou, 2022; Lee & Wan, 2022; Macnaught, 2021; Mouton, 2019).

Positioning knowledge-building practices at the center of learning and teaching, LCT comprises five dimensions: autonomy, density, specialization, temporality, and semantics (Maton, 2014a). Each dimension and its specific concepts can be used separately depending on the problem and questions of the study. I focus only on the dimension of semantics for two reasons. First, the dimension of semantics emphasizes the importance of interactions between meanings and contexts (Maton, 2014a). Second, the other dimensions do not directly capture the issue of condensation of meaning that is at the heart of the recontextualization of knowledge (Bernstein, 2000) and that is central to the type of modeling explained in the Instructional Context section and depicted in Figure 5. Thus, this study gives serious consideration to the dimension of semantics, to which I now turn.

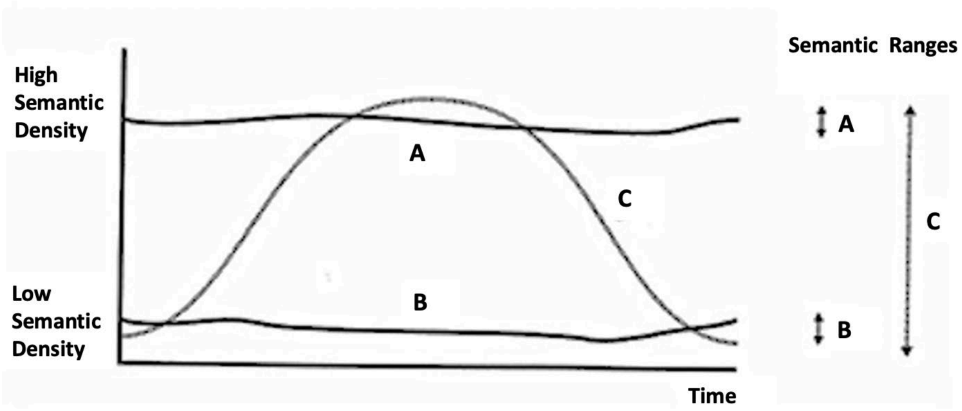
Semantics is one of the dimensions of LCT that considers social fields of practice as semantic structures whose organizing principles are conceptualized as semantic codes, centering around strengths of semantic gravity and semantic density (Maton, 2013). Semantic gravity refers to “the degree to which meaning relates to its context (context-dependence)” (Maton, 2013, p. 11). Semantic density (SD) examines the complexity and technicality of meanings, such as the condensation of meanings within symbols (a term, concept, phrase, expression, and gesture) (Maton, 2013). For instance, the concept of dissolution is represented by a chemical equation, [$NaCl(s) \rightarrow NaCl(aq)$]. Dissolution is an abstract concept represented by elements and symbols (high semantic density) (Blackie, 2014). Within the equation, a large amount of information is condensed into symbols. The stronger the semantic density, the more meanings are condensed within symbols, words, expressions, or gestures; the weaker the semantic density, the fewer meanings are condensed (Maton, 2013). Semantic density centers around complexity: the stronger the semantic density, the more complex the meaning of the semantic structure. A growing number of researchers and educators have addressed the importance of embedding the concepts of semantics (semantic gravity and semantic density) in their research, pedagogy, curriculum, and assessment to gain insight into how learning can be supported in areas including history (Matruglio et al., 2013), chemistry (Blackie, 2014), physics (Georgiou, 2014; Georgiou et al., 2014; Lindstrøm, 2010; Steenkamp et al., 2019), biology (Mouton & Archer, 2019), teacher education (Macnaught, 2021; Shalem & Slonimsky, 2010), environmental science (Tan, 2012), political science (Clarence, 2016), English (Kirk, 2017), and science teaching practices (Doran, 2021).

This study focused on semantic density, as I was most interested in examining how multimodal modeling practices can help learners pack and unpack meaning in knowledge building in science. In using the concept of semantic density to examine the constructs, I focused specifically on packed and unpacked meanings. Packing refers to condensing meaning or going from simpler and contextualized meanings to more condensed, complex, or technical meanings, whereas unpacking goes the opposite way (Clarence & van Heerden, 2021). In science, for instance, when a term or concept, such as friction, is used, the meaning is usually relatively condensed, complex, technical, and packed. When the meaning is explained with everyday language or simpler terms, it is unpacked (Mouton, 2020). As an example of unpacking the meaning of friction, when two surfaces slide against each other, friction makes them stick very slightly together. Creating very little friction, smooth surfaces like ice are easy to slide over while rough surfaces like rock create much more friction and are easy to grip on to. Shifting between condensed, complex (packed) meanings and simpler, contextualized meanings (unpacked) is important for effective and productive knowledge-building practices (Maton, 2013). In what follows, I explain how semantic density functions in instructional practices and why it is important for knowledge building in science.

According to Maton (2013), semantic density can be strengthened by moving from a term that implicates simpler and contextualized meanings to one that includes condensed and complex meanings. Conversely, semantic density can be weakened by moving from a term with highly condensed meanings to one that implicates simpler meanings—unpacking technical terms into simpler terms leads to the semantic density of the knowledge being expressed to be weaker (Maton, 2014a, 2020). Maton visualized how the strengths of semantic density vary over time by developing a method of semantic profiling. Adapted from Maton (2013), Figure 2 represents three distinct semantic profiles. The semantic range is defined as the range of semantic density between its highest and lowest strengths (Maton, 2013). In Figure 2, the y-axis represents the respective strengths of semantic density, while the x-axis shows time. The semantic profiling may vary in time (e.g., a short classroom episode, a student task, an entire lesson, or a whole curriculum). What Maton represented in Figure 2 is a high semantic flat line (A), a low semantic flat line (B), and a semantic wave (C). Figure 2 also shows that A and B have lower semantic ranges than C, as indicated on the right-hand side. Semantic waves refer to recurrent shifts in the condensation of meaning (Maton, 2014b).

Figure 2

An Illustrative Semantic Density Profile and Its Range



The challenge in any teaching context is to shift between the more technical and the less technical terms, concepts, and ideas in knowledge building (Maton, 2009). This shift is important for learning and represents a key characteristic of knowledge building (Maton, 2011, 2014b). Regarding the importance of these ongoing downward and upward semantic shifts, Maton's analysis of classroom practices revealed that pedagogical activities comprise a series of downward semantic shifts—what he calls a down escalator profile—in which teachers tend to unpack and simplify technical terms and concepts and relate them to students' everyday lives (Maton, 2013). The reason for observing a down escalator profile in classroom practices is that teachers hardly facilitate the process of shifting upward by condensing meaning into symbols, terms, and concepts or making connections between everyday examples and theoretical ideas (Maton, 2013, 2020). It is also possible to observe the opposite pedagogical practices that center around upshifting, as Shay and Steyn (2015) explained how some pedagogical practices emphasize only theoretical ideas.

I now share some examples showing how meanings may be transformed through semantically weaving together different forms of knowledge: simpler, contextualized meanings and condensed, complex, technical meanings (Maton, 2013). The first example is from Macnaught et al.'s (2013) investigation into how teachers can be trained to enable cumulative knowledge-building. Their study addressed how teachers help students construct a wide range of specialized biological meanings in the classrooms. The authors used the dimension of semantics in teacher training to explore the scope of knowledge building by analyzing students' exam responses collected in a high school biology classroom. Students were asked to briefly describe the process and role of mitosis. Table 1 and Figure 3 (both adapted from Macnaught et al., 2013, p. 52) represent the exam responses of two students and the semantic profiles of the responses respectively.

Table 1

Sample Student Responses, Adapted from Macnaught et al. (2013, p. 52)

Student A	Student B
Mitosis is when the two parent cells come together, their DNA replicates and all these cells then replicate again which goes on to form two diploid cells. The 23 pairs of chromosomes combine to make it all up. All chromosomes contain the same genetic material that helps generate the body. Mitosis replicates the chromosomes which create enzymes.	Mitosis is one of the two forms of cell division that occurs in our body, the other being Meiosis. Mitosis is the process in which a cell divides into two cells identical to the original cell. Mitosis begins with DNA replication. This is when the cell's chromosomes replicate and split. The cell then divides into two cells each with 46 chromosomes, otherwise known as diploid cells. Mitosis is used for many processes in our body involving growth and repair.

Figure 3

Students' Explanations of Mitosis in Semantic Waves, Adapted from Macnaught et al. (2013, p. 52)

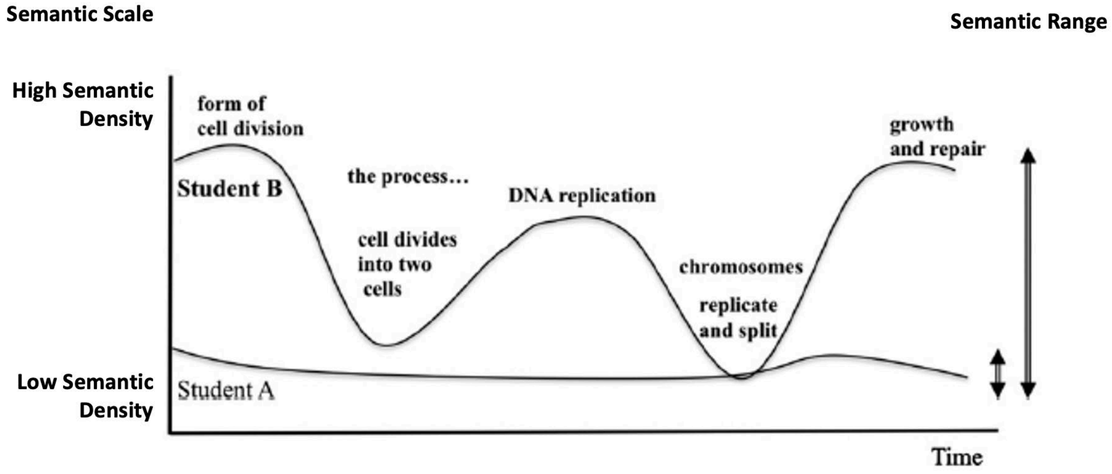


Figure 3 shows that Student B begins with higher semantic density by introducing the term mitosis (condensed meaning) and locating it as a more general type of process (i.e., one of the two forms of cell division). Next, the student defines mitosis by outlining what mitosis is and the result of it (i.e., cells dividing into two), which leads to weaker semantic density (unpacking the meaning). Student B continues with a similar pattern in which the process of DNA replication is defined and then the description of cell components and processes involved is provided (i.e., chromosomes replicate and then cells divide). Student B completes the answer by moving upward towards stronger semantic density by mentioning the general functions of mitosis in the human body (i.e., growth and repair).

As shown in Figure 3, Student B's answer represents a complete semantic wave. Conversely, because of a limited range of meanings, Student A's semantic profile represents a low semantic flat line. The key reason for this is that the answer does not represent a shift between packed and unpacked meanings. Student A's response tends to unpack and simplify technical terms (e.g., mitosis) and is stuck in a semantic range that is limited to weaker semantic density.

The second example is from Mouton's (2020) work on examining when and how semantic shifts happen throughout a project-based learning experience in a first-year biology classroom. Focusing on the first-year biology students' project presentations, the study aimed to show how students display movements between context-dependent, simpler meanings, and relatively decontextualized, condensed meanings during their presentation. The semantic profiles of the student presentations showed regular shifts in semantic density throughout the presentations. Students shifted between less complex and more complex meanings by elaborating on condensed meanings using simpler terms, phrases, and visuals, for example:

> …the toxin has a light chain and a heavy chain. Let me explain the light chain and the heavy chain quickly. The heavy chain allows the protein to bind to and enter the neuron as you can see (student points to a diagram). As the heavy chain allows entry, the light chain, which is the smaller one (student points to a diagram), works as a protease and cleaves the proteins that allow the neurotransmitters to leave the cell. So, basically, it chops it up and makes it inactive… (Mouton, 2020, p. 377)

In this example, the student presentations showed shifts in the complexity of meanings. Students used shifts in semantic density when explaining complex meanings to their peers in the classroom. For instance, students used a diagram to unpack the meaning of the heavy chain and its function and some phrases to unpack the meaning of the light chain and its function by using the phrases "chop it up" and "make it inactive".

The last example is from Maton (2013, p. 15) explaining a semantic wave created in a discussion on biological lines of defense, focusing on cilia:

Teacher: Okay [student name] what are the cilia? What was it? No? [Student name] do you know what cilia is? No? Someone must know what they are…

Student: Hairs

Student: The little hairs?

Teacher: The little hairs. And basically, they beat in an upward motion from inside your body out through to your nose [Teacher is waving arms upwards]. So, they beat up and take the pathogens away with them. And, guys, I don't know if I've ever told you this, but when you smoke cigarettes, the tar actually causes your cilia to, because it's so heavy, drop, and so your cilia don't work properly after that because they're too heavy, they've dropped, so they can't beat the pathogens out of your body! So that's one reason that smoking's bad as well. Okay! Alright, write this down under the description!

In this classroom interaction, the teacher begins by introducing a scientific term, cilia, that condenses a wide range of meanings in biology. With help from students, the teacher then unpacks some of the meanings of cilia by using phrases from everyday language (e.g., the little hairs) and embodied actions (e.g., waving arms). The teacher also mentions smoking as an additional concrete example from everyday life. This phase of the instruction is called unpacking, leading to simpler and contextualized meanings (Maton, 2020). This unpacking provides students with a point of entry into complex, condensed, and technical meanings. Next, the teacher starts packing the meanings into the term by writing the following statements on the board:

Line of defense	Description	What it does
cilia	Hair-like projections from cells lining the air passages	Move with a wavelike motion to move pathogens from the lungs until they can be swallowed into the acid of the stomach

This is not a summary of the unpacking mentioned earlier. Instead, the teacher packs the term, cilia, by decontextualizing the meaning (i.e., smoking is no longer mentioned). The term, cilia, reaches beyond the term itself and is positioned as a line of defense along with other lines of defense presented in Table 2.

Table 2

The Teacher's Table Entry for Lines of Defense, Adapted from Maton (2013)

Line of defense	Description	What it does
Skin	Skin continuously grows by new cells being produced from below. Cells fit tightly together to form a protective layer covered by dead cells.	When unbroken skin prevents the entry of pathogens. Pores in the skin secrete substances that kill microbes. Skin constantly flakes off carrying microbes away. It is a difficult environment for a pathogen to grow (no water).
Mucous membrane	Cells lining the respiratory tract and opening the urinary and reproductive systems secrete a protective layer of mucous.	
Cilia	Hair-like projections from cells lining the air passages	Move with a wavelike motion to move pathogens from the lungs until they can be swallowed into the acid of the stomach
Chemical barriers	The acid in the stomach, alkali in the small intestine, and the enzyme lysozyme in the tear	Stomach acid destroys pathogens including those that are carried to the throat by cilia and then swallowed. Alkali destroys acid-resistant pathogens. Lysozyme dissolves the cell membranes of bacteria.
Other body secretions	Secretions from sweat glands and oily secretions from glands in hair follicles	Contain chemicals that destroy bacteria and fungi

This downward (i.e., unpacking) and upward (i.e., packing) semantic shift achieve one form of a complete semantic wave that crosses gaps in instruction, as emphasized by LCT (Maton, 2013, 2014a, 2020). Semantic density offers the possibility of investigating formations and transitions of knowledge from contextualized and simpler meanings toward more complex, condensed, and technical meanings (Maton, 2014a).

Based on the elaboration of the theory above, this study expects that the LCT semantics helps in understanding two aspects of knowledge-building practices that are focused on in this study: the complexity and technicality of meaning and the shift between everyday language and scientific language. Semantic density is neither definitional nor definitive (Maton, 2020). The forms taken empirically by semantic density are different in each object of study and for each form of data. Accordingly, the research develops analytical schemes that translate this concept within specific objects of study being explored (Maton, 2020). Using semantic density in a study entails tailoring this concept in such a way specific research questions can be answered (Lee & Wan, 2020). In this way, I used this concept, semantic density, to frame the constructs used in this study and analyze my data from a different lens to generate knowledge about multimodality, language, and modeling. This concept helped me extend my thinking about crafting a qualitative description and explanation of knowledge building beyond an easy sense (e.g., patterns/themes produced by coding data with reductive and deficit perspectives and languages) that is not creative, varied, and non-formulaic.

CHAPTER 3

METHOD

Study Design

This is a case study of a group of preservice elementary science teachers engaging in multimodal modeling practices to understand the concept of the transfer of energy in glycolysis. In this section, I situate the use of a case study in this research and discuss other elements of the study design, including site and participant selection, instructional context, data collection, data management, data analysis, and data quality.

Case Study

Merriam's (2009) and Stake's (1995) view of case study guided the research design. Merriam (2009) defines three unique distinctive attributes of a qualitative case study: (a) particularistic—illuminating a particular situation, event, program, or phenomenon, (b) descriptive—generating a thick description of the phenomenon of interest, (c) heuristic—helping the reader understand the phenomenon of interest. This study was designed as a case study to explore the complex issue of knowledge building through multimodal modeling practices. The case was bounded (a modeling lesson), instrumental (insight into a specific issue of knowledge building), and context-specific (a science methods course) (Merriam, 2009).

Designed as an instrumental case study, this qualitative investigation enabled the exploration of knowledge building of a group of preservice elementary science teachers engaging in learning about the transfer of energy in glycolysis with multimodal modeling practices. According to Stake (2005), an instrumental case study allows researchers to gain insights into individuals' experiences or views of a phenomenon. Stake (1995) described such case studies in this way:

> We have a research question, a puzzlement and a need for general understanding, and feel that we may get insight into the question by studying a particular case… We may choose a teacher to study, looking broadly at how she teaches but paying particular attention to…[a particular aspect of her teaching]… The case study here is instrumental to accomplishing something other than understanding this particular teacher, and we may call our inquiry instrumental case study. (Stake, 1995, p. 3)

Attending to both Stake and Merriam's arguments, I selected an instrumental case study design because I sought to investigate how preservice elementary science teachers built knowledge as they engaged in multimodal modeling practices to understand the transfer of energy in glycolysis. The case was bounded by a group of preservice elementary science teachers' knowledge building through a unit of modeling-based instruction about glycolysis in two sections of a science methods course that I taught throughout two 50-min class periods during the spring semester of 2021. The case was further bounded in that it was the first time that student teachers engaged in multimodal modeling practices to learn about cellular respiration.

Site and Participant Selection

I conducted this case study with two of the three cohorts of preservice elementary teachers registered for a science methods class as part of the third block of their program curriculum during the spring semester of 2021 at a large public university in the southeastern United States. As stated in the Elementary Education Program Student Handbook (the version edited in 2020), the program curriculum prepares teachers of prekindergarten through fifth grade to produce educational knowledge and apply it to benefit children, families, and communities in diverse and inclusive educational settings.

After the approval of all methods and procedures in this study by The University of Georgia Institutional Review Board on Human Subjects (see Appendix A), I explained the study to all members of the cohorts (a total of 46 preservice teachers) and allowed them to participate in the study. Only those who consented to all aspects of data collection (i.e., classroom videos, audio recordings, and interviews) and their artifacts (worksheets, drawings, and reflective essays) were included in the data sets that were analyzed. I was also granted permission to use photos of some participants regardless of whether they are identifiable. 33 preservice teachers consented to audio and video recording of the modeling instruction, 17 learners consented to interviews, and 12 learners granted permission to use their reflective essays as data sources in this study. After the classroom instruction, I conducted think-aloud interviews with a subset of the participants. The sampling method for the think-aloud interviews was purposeful sampling, also called purposeful selection or purposive sampling. Purposeful sampling is “selecting information-rich cases for study in-depth” (Patton, 2002, p. 230). Purposeful sampling helps researchers select particular settings (e.g., observation settings) or persons (e.g., interview participants) that provide rich information relevant to their research questions (Maxwell, 2013). Based on Patton’s further classification of purposeful sampling, this study used criterion sampling. Criterion sampling scheme (Onwuegbuzie & Leech, 2005) is a process by which researchers select participants for a series of data collection procedures or a specific part of it because they meet one or more criteria. For this study, I was interested in interviewing learners who (a) were highly motivated to learn, (b) actively engaged in the practice of modeling during classroom instruction, and (c) consented to all aspects of data collection. Based on these criteria, I interviewed 10 learners who reported a background in science, reported a background on learning about cellular respiration and through modeling, and reported perception of scientific language are presented in Table 3.

Table 3

Self-Reported Background of Learners

Name	Science classes that are taken in high school	Prior experience learning cellular respiration	Prior experience learning models and/or modeling	Perception of scientific language
Robert	Biology Chemistry Physics Environmental Science	No	No	"Boring"
Luci	Biology Chemistry Physics Environmental Science	Yes: Textbook-based instruction	No	"Overwhelming" "Confusing"
Laura	Biology Chemistry Physics Forensics Anatomy	Yes: Video- and worksheet-based instruction	No	"Definitions" "Vocab"
Anna	Biology Chemistry Physics Environmental Science	Yes: Nothing to recall	No	"Kind of like a foreign language"
Melissa	Earth Science Biology Chemistry Physics	Yes: Worksheet-based instruction	No	"Overwhelming" "Discouraging"
Taylor	Biology Chemistry Physics Environmental Science	No	No	"Memorize terms and definitions"
*Diane	Biology Chemistry Physics Anatomy	Yes	Yes-Physical models	"Definition learning"
Edna	Biology Chemistry Zoology Physics	Yes: Worksheet-based instruction	No	"Decoding scientific terms"
Sally	Physical Science **AP Biology **AP Chemistry Animal Science	Yes: Video- and worksheet-based instruction	Yes-Physical models	"Not always necessary"

Name	Science classes that are taken in high school	Prior experience learning cellular respiration	Prior experience learning models and/or modeling	Perception of scientific language
Mary	Biology Chemistry Physics Anatomy	Yes: Worksheet-based instruction	Yes-Physical models	“Complicated” “Confusing”

Note. Names listed are pseudonyms selected by the participant. Individuals are presented in the order in which they were interviewed.
*Diane indicated that she has a speech disorder called stuttering.
**AP: Advanced Placement

None of the learners had any previous experience learning science with the type of models and modeling employed in this study. Even though all of them took a high school biology class, their prior experience learning about cellular respiration was either very limited or they did not remember learning about it. This was evident in the following dialogue between learners and me at the beginning of the instruction.

Ayça: What do you think respiration is?

Learners (about half of them answered at the same time, the other half remained silent): Breathing.

Ayça: What do you think cellular respiration is?

Learners: Cell breathing.

This points to a naïve conception of cellular respiration. Cellular respiration is the breakdown of glucose (sugar) into carbon dioxide and water in our cells, releasing energy, whereas breathing involves inhale of oxygen from the atmosphere into the lungs and exhale of carbon dioxide from the lungs into the atmosphere.

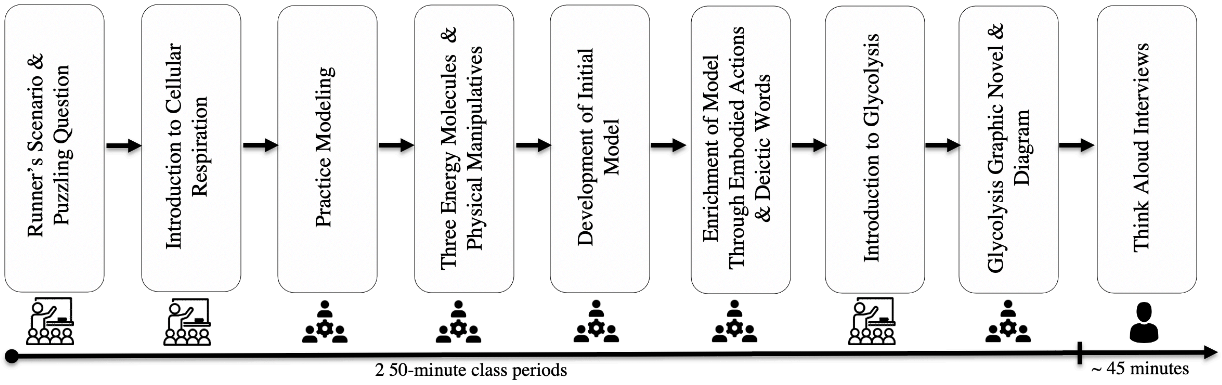
Instructional Context

I adopted and implemented a modeling-based unit about cellular respiration that was developed as part of a larger research project (see Appendix B or click on this link). The unit was designed for high school biology students and emphasized the Next Generation Science Standards' practice of scientific modeling. The modeling-based lesson aimed to help learners understand the big picture of cellular respiration, namely the transfer of energy, by engaging them with modeling practices. Figure 4 presents an overview of the activities implemented in this study.

The unit began by introducing students to the Meet the Runners scenario in which a sprinter and a distance runner were compared in terms of their performance and a puzzling question was raised: What happens differently inside the distance runner's body that helps her run farther than the sprinter? While learners were thinking about this question, the lesson started eliciting their prior knowledge and concepts about cellular respiration by discussing what cellular respiration was and how and where the human body converted glucose (a type of sugar) into energy. Then, the lesson brought learners back to the scenario and provided some metabolic parameters (oxygen used, glucose used, lactic acid produced, and mitochondrial volume in leg muscles) in a table to help them answer some questions to explain the differences between the sprinter and the distance runner.

Figure 4

Overview of Activities



🧑‍🏫 = whole class, 👥 = small group, 👤 = individual

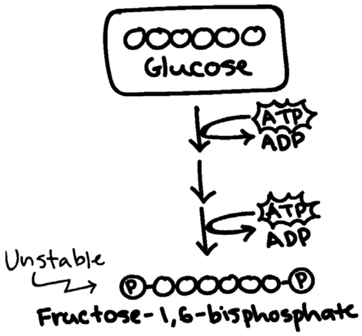
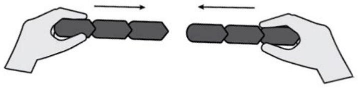
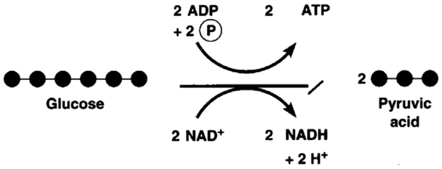
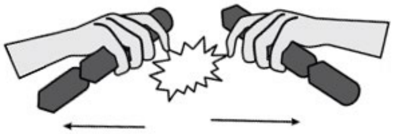
Following the introduction, learners engaged in a modeling practice activity in which they learned how to develop abstract representations by comparing two or more examples of a phenomenon or object that differed on the surface but shared an underlying structure. They were asked to draw a general model that stood for (a) teacup, spoon, and watering can, and (b) watermelon, earth, and a candy bar. This step was important for learners to get familiar with the specific way of modeling used in this lesson, namely inductive modeling (explained in the Inductive Modeling section).

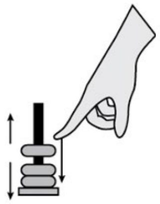
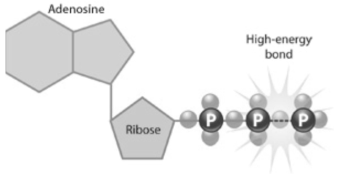
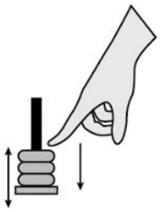
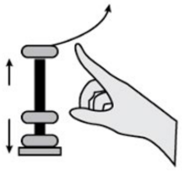
The next step was introducing the main energy molecules in cellular respiration: Glucose, ATP (Adenosine triphosphate), and NADH (Nicotinamide adenine dinucleotide). To learn about each energy molecule, learners were provided with a story card introducing each energy molecule, its parts, and a narrative on how the molecule could assemble, remain assembled, or break into constituents. The stories related the molecular configurations (metaphorically assembling and disassembling the parts of the molecules) to getting, having, or releasing energy. The idea of getting, having, or releasing energy became the underlying structure that learners developed a model of later in the learning process. They then enacted three different energy stories with the physical manipulatives, one for each molecule. The glucose manipulative consisted of six plastic beads that were attached (see Table 4). Between the beads, there were small firecrackers, small explosive devices that produce a small bang. The six plastic beads represented six carbon atoms in glucose. The small firecrackers represented the energy released when the glucose was split into two molecules. When six plastic beads are attached, a glucose molecule is formed. The ATP manipulative was a floating ring magnet set including three ring magnets and a stand (see Table 4). Three ring magnets represented three phosphate groups, and the stand represented the adenine base (and a ribose sugar) in ATP. When all three magnets were attached, ATP was formed. Removing the third magnet from the magnet set turned ATP into ADP. The manipulative for NADH was a novelty snake-in-a-can that included four components: the can, lid, spring, and two cotton balls (see Table 4). The can represented NAD+, the spring represented the action of chemical bonds within NAD+, the lid represented H- (hydrogen), and two cotton balls represented electrons. To produce NADH, the spring and cotton balls had to be stuffed into the can (NAD+) before the lid (hydrogen) was placed over, to hold everything in. To reverse this process, the lid was removed, and the spring and electrons jumped out of the can.

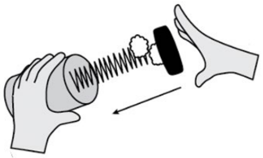
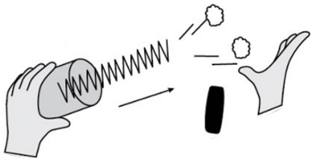
Each physical manipulative provided learners with the haptic (involving the sense of touch) experience of applying or releasing a force to change the energy state of the molecules. For instance, to show how those three molecules get energy, they forced a set of plastic beads (carbon atoms) together (for glucose), forced three magnet rings (phosphates) against each other (for ATP), and squeezed a spring into the can (for NADH). The manipulatives helped learners use the concept of forcing materials (molecules) together (e.g., forcing a set of plastic beads together). In reality, it might be better to think of it as pulling the materials away from a preferred configuration to represent the change in the level of energy of molecular entities (e.g., three phosphate molecules in ATP). In this study, the concept of energy was taught through the substance metaphor for energy as explained in the Teaching the Concept of Energy section. Table 4 presents an overview of how glucose, ATP, and NADH get, have, and release energy biologically vs. metaphorically. The column titled Metaphorically in Table 4 represents how participants learned about the concept of energy in this study.

Table 4

Molecules Getting, Having, and Releasing Energy

		Biologically	Metaphorically
Glucose	Getting	The generation of glucose is called gluconeogenesis, and it is an endergonic process that requires the absorption of energy. A version of this process occurs in plants and is called photosynthesis. As a specific example from glycolysis, two phosphate groups are attached to glucose, making it *unstable and allowing it to split in half.  Photo credit: Khan Academy	Six plastic beads represent six carbon atoms in glucose. When six plastic beads are attached, a glucose molecule is formed. 
	Having	Glucose has energy stored in its chemical bonds.  Photo credit: Khan Academy	Once six carbon atoms are together, glucose stores energy. 
	Releasing	Energy is made available by the breakdown of sugar (glucose). The overall result of the process is to yield energy, and it is in this sense that the breakdown of sugar is described as releasing energy.  	***Splitting glucose in half releases some energy stored in the bonds. 

		Biologically	Metaphorically
ATP	Getting	ADP can be recycled into ATP by forming a new high-energy bond (called phosphoanhydride bond) to store energy. ATP molecules are just like rechargeable batteries. $\text{ATP} \leftarrow \rightarrow \text{ADP} + \text{P} + \text{energy}$	Three floating ring magnets represent three phosphates in ATP. Adding a third magnet to the two magnets on the base turns ADP (includes two phosphates) into ATP (includes three phosphates). 
	Having	ATP has three phosphate groups that are linked to one another by two high-energy bonds. The high-energy bonds are the key to ATP's energy storage potential. 	When all three magnets are attached, ATP is formed. 
	Releasing	**Hydrolysis (water-mediated breakdown) of ATP: When one phosphate group is removed by breaking a phosphoanhydride bond between phosphate groups, energy is released, and ATP is converted to adenosine diphosphate (ADP). $\text{ATP} + H_2O \rightarrow \text{ADP} + P_i$	When the third magnet is removed from the magnet set, ATP releases energy and turns into ADP. 

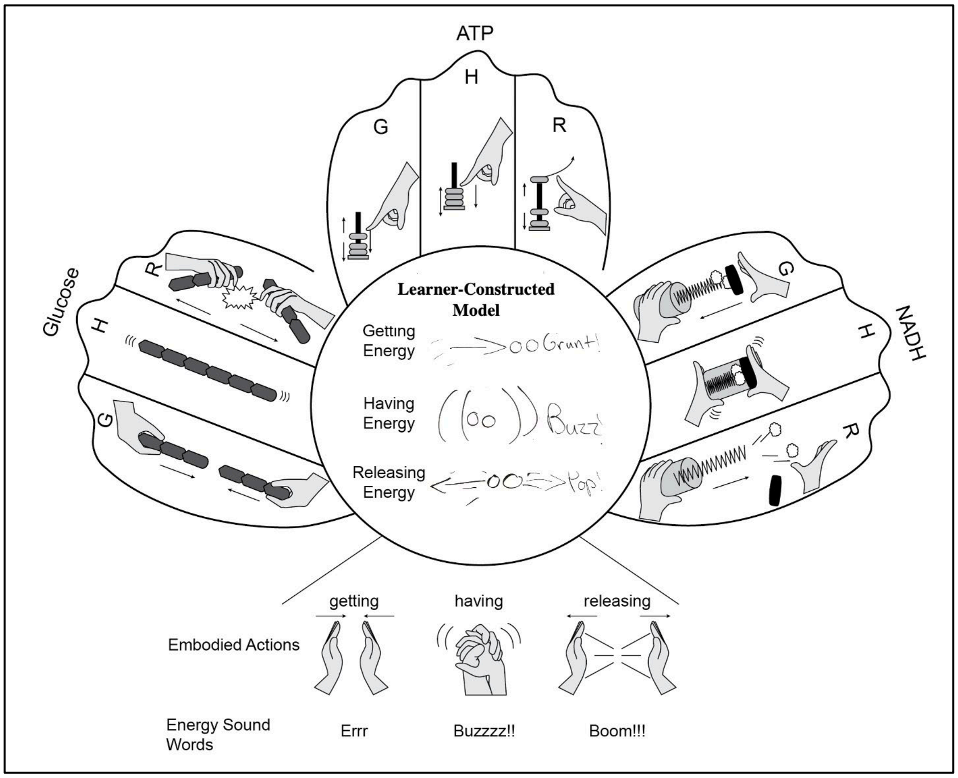
		Biologically	Metaphorically
NADH	Getting	When NAD is converted to NADH, it gains two things: First, a charged hydrogen molecule (H+), and next, two electrons. NADH transports these electrons to mitochondria where the cell can take the energy that is stored in the electrons. NAD + H + 2e → NADH	The can, spring, and cotton balls represent NAD, H, and two electrons respectively. Once the spring and two cotton balls are squeezed into the can, NADH is formed. 
	Having	NADH is a high-energy molecule, and it can be used as a reducing agent by the cell. But much of the stored energy is not directly accessible to the cell in this form.	The can, including the spring and cotton balls, is a source of high energy. 
	Releasing	NADH plays a key role in the production of energy through redox reactions. In redox reactions, NADH molecules are split into NAD, producing H and a couple of electrons. NADH → NAD + H + 2e	When the spring and two cotton balls are removed, high energy is released from NADH. 

Note. *In biology, the term unstable is used to describe the state in which molecules have negatively charged groups or compounds attached to themselves. For instance, phosphate groups in ADP and ATP are negatively charged and thus repel one another. This repulsion makes the ADP and ATP molecules inherently unstable. The release of one or two phosphate groups from ATP, a process called dephosphorylation, releases energy. Dephosphorylation is the removal of a phosphate group from an organic compound by **hydrolysis (Molnar & Gair, 2015).
***In reality, the energy release does not happen upon breaking, but upon the formation of a new molecule. To avoid any naïve conception about this, during instruction, I discussed what happens in reality vs. why we talk about the energy release in a way that is described in Table 4. Please see the Teaching the Concept of Energy section for more details on how the literature talks about this naïve conception.

Next, learners were asked to develop their initial model to explain how these three energy molecules get, have, and release energy to facilitate the energy transfer in cellular respiration. Students in small groups worked on their model and shared it with the whole class so that they had a chance to negotiate between their way of thinking about the phenomenon and those of others as part of the knowledge-building conditions mentioned earlier in this study. Additionally, working in a small group better encouraged them to try to make their process of knowledge building visible than when they were in a whole class setting (Singer et al., 2008). After learners developed their initial model of the underlying structure that was abstracted from the three source phenomena (glucose, ATP, and NADH), they enriched their model by incorporating a set of embodied actions and energy sound words that they generated into their model. For instance, to represent releasing energy, they might let their hands fly apart and generate explosion noises. It is known from research on embodied learning (e.g., Lindgren & Johnson-Glenberg, 2013) that embodied actions help learners represent ideas and concepts efficiently and effectively. Additionally, learners were asked to generate energy sound words (deictic words) to represent each molecule obtaining, holding, and releasing energy by using everyday language (e.g., "boom", because releasing energy is caused by molecules breaking apart). By using embodied actions and deictic words, they were expected to enrich their model and condense the meanings that emerged from their experience.

Figure 5

A Learner-Constructed Model of Energy Transfer in Cellular Respiration



G: Getting energy, H: Having energy, R: Releasing energy

Following the development and enrichment of learner-constructed models (see an example of a learner-constructed model in the center of Figure 5), the lesson introduced glycolysis, the first metabolic step in cellular respiration, to learners as part of the formal instruction. First, learners watched a short animation that zoomed in on a muscle cell and explained what happened with the energy molecules during glycolysis. Then, they were given two expository texts (informational texts), in the form of a graphic novel and a diagram, describing the steps of glycolysis (see Appendix B or click on this link). They were asked to process these texts by identifying where the energy molecules got, had, or released energy. Since these two science texts contained different linguistic features and functions, this phase in the instruction was expected to help learners formalize their knowledge and comprehend the information presented in the science texts (Snow, 2010; Van den Broek, 2010). Working in small groups, learners processed these two texts by writing margin annotations to interpret events involving glucose, ATP, and NADH. Learners' annotations referred to the energy processes (or deictic words) in their model (i.e., getting energy as "crunch", having energy as "buzz", or releasing energy as "boom"). It meant learners used their model to think with while they processed these two texts. After they completed these two texts, I went over their annotations by discussing and resolving any questions or differences and ended the formal instruction about glycolysis.

The Approach to Modeling in the Instructional Context

The type of modeling used in this study is called synthesis modeling. Synthesis modeling is described as seeking the underlying structure from two or more scenarios that contain it (Capps & Shemwell, 2020). When developing a model through synthesis modeling, learners are asked to work from two or more instances of a phenomenon that share an underlying structure but differ on the surface and abstract the structural similarities embedded in those instances (Capps & Shemwell, 2020).

Synthesis modeling is guided by the theory of analogical learning (Gentner, 1983; Gick & Holyoak, 1980; Johnson-Laird, 1983). Analogical learning entails "examples (as few as two) that are not particularly similar in semantic and perceptual features" (Holyoak & Lee, 2017, p. 459). Analogical learning explains how learners can formulate abstractions by seeking the common structure within scenarios that are similar in essence but differ on the surface (Catrambone & Holyoak, 1989; Gick & Holyoak, 1980). This means that individual components in the multiple scenarios might be semantically quite different, but the structural relations between those components are similar across the scenarios. Analogical thought should help learners abstract and map correspondences between multiple scenarios and apply them to a new domain (target) by using the selected ideas. Because analogies involve rich relations (the complexity of the relations), abstraction ranges from low to high depending on the use of superficial similarities or key structural (relational) similarities over multiple examples (Holyoak et al., 2010).

Induction is one of the philosophical foundations for the use of analogies (Bartha, 2013). Induction “uses observations to arrive at premises as well as relations between premises, which are then used to arrive at conclusions” (Nunes, 2012, p. 2066). Most explanations in the sciences, in particular biology and medicine, entail inductive processes (Schaffner, 1994). Using inductive processes is an important approach to developing scientific explanations of natural phenomena (e.g., Kuo & Wieman, 2016; Yanowitz, 2001). Similarly, learning the underlying structure of a mechanism, system, or event requires an inductive process in which learners conjointly observe multiple cases of a phenomenon and abstract the structural similarities (Gentner, 1983; Gick & Holyoak, 1983). For instance, Capps and Shemwell (2020) conducted a study in which high school students adapted an inductive approach to model construction to develop a model of how deserts form by simultaneously observing two different examples of deserts (a rainshadow desert and a trade wind desert) and abstracting the common underlying structure that illustrates the air and moisture transport.

Importantly, I am not making the argument that induction is a better approach for developing models in science. Rather, the specific type of modeling (in this case, synthesis modeling) on which my recent study centers entails an inductive process so that model development can provide learners with a stable structure that can be abstracted from multiple scenarios representing the same phenomenon and applied to novel situations in science learning.

This inductive approach to model construction supports learners in abstracting that stable structure by simultaneously observing multiple sources of the phenomenon of interest (Capps & Shemwell, 2020).

The Conceptualization of the Transfer of Energy in the Instructional Context

Energy is one of the key concepts in science. In the Next Generation Science Standards (NGSS) and the Framework for K-12 Science Education, the concept of energy is considered both a disciplinary core idea and a crosscutting concept (NGSS Lead States, 2013; NRC, 2012). These two educational reform documents call for K-12 students to develop their conceptual understanding of energy across both grade levels and disciplines. Even though the concept of energy is important to learn in science, the concept is highly challenging for students to conceptualize across all grade levels. Research on students learning about energy points to two main challenges. First, the ways of teaching about energy fall short of promoting integrated understanding (Linn & Eylon, 2006). Second, students hold several alternative conceptions about the concept of energy—energy as an accounting system, flow, loss, ingredient, product, interaction, and so on (Lancor, 2014; Leggett, 2003).

While much pertinent research has been done regarding students' learning of the energy concept (i.e., learning progression of energy), this study is unique in two ways. First, the concept of energy is context-specific (cellular respiration)—knowledge is not domain-independent but is somewhat specific to the task at hand (Singley & Anderson, 1989)—so that students can learn how to communicate the energy idea in a disciplinary (in this case, biology) way of knowing, (Airey & Linder, 2009). It means the process of learning is situated in specific contexts and thus what is learned cannot be detached from the situation in which it is learned (Brown et al., 1989). Second, the concept of energy is built through modeling experiences in which students learn about the useful underlying structure—the three energy processes: getting energy, having energy, and releasing energy. Through their modeling experiences, students are expected to develop representations of these energy processes, the transfer of energy, in this study.

In different fields and scenarios, different aspects of energy are studied and represented. For instance, while in chemistry and physics, energy is studied and examined at the microscopic (molecular) level, in biology energy is understood at the macroscopic level (Cooper & Klymkowsky, 2013).

There are different ways to conceptualize energy based on the scientific field.

> A particle physicist talks about the mass of a particle in terms of its energy, highlighting the mass-energy equivalence principle. Ecologists discuss how 90% of the energy in a system is lost between trophic levels, emphasizing energy degradation. To a chemist, chemical bonding is determined by a molecule's favorable energy states. (Lancor, 2014, pp. 1-2)

Even within a given discipline, energy is conceptualized in different ways depending on the specific contexts (Cooper & Klymkowsky, 2013).

The studies in chemistry education research discuss how students hold naive conceptions about the concept of energy due to the differences between the approaches to teaching about energy across disciplines (e.g., Cooper & Klymkowsky, 2013; Teichert & Stacy, 2002). For instance, one dominant conception of energy is that when bonds in a molecule break, the molecule releases energy. In chemistry and physics, this idea is problematic and a misconception (Cooper & Klymkowsky, 2013). Becker and Cooper (2014) argued that one reason for associating bond breaking with the release of energy is that potential energy is framed as stored energy, captured energy, or energy in food in textbooks and even in the framework for K-12 science education (see <u>the standard</u> for elementary level and <u>the standard</u> for high school level) (NRC, 2012).

"A key part of what an energy representation articulates is what kind of thing energy is (its ontology)" (Scherr et al., 2012, p. 020114-1). Regarding ontology, energy is identified as a metaphorical substance in this study because a substance metaphor for energy best supports learning about the transfer of energy within, into, or out of systems of objects (Scherr et al., 2012). According to this ontology, "energy is infused into objects the way tea flavor is infused into the water. . .This image retains the sense of energy as a kind of stuff that can be in objects (as a fluid is in a container)" (Scherr et al., 2012, pp. 020114-3-4).

Using the substance metaphor for energy, this study has two assumptions about the concept of energy and its representation: (a) energy is in objects, and (b) energy is transferred among objects. Thus, the transfer of energy focuses on the physics of reactions—e.g., molecules change their energy levels through an applied force—rather than the chemical aspects of the reactions. The specific characteristics of the substance metaphor for energy such as "being containable, localized, movable, additive, and conserved" are intuitively accessible for students, and they are easy to conceptualize (Scherr et al., 2012, p. 020114-6). These characteristics allow students to locate the energy in isolated objects as is appropriate to the learning goals and nature of the modeling instruction. Because models are abstract, partial renderings, all models leave out certain details and information in their representation of a concept or system. The ways a model is developed may offer (more or less) abstract characterizations of a phenomenon. All models are incomplete and inadequate to represent all aspects of a system, but they are still models of a particular system (Johnson-Laird, 1983; Passmore et al., 2014). We may have two models representing the same concept. The first model may fall short in explaining certain aspects of the concept, while the second model can explain what is missing in the first one and be still inadequate to explain other aspects of the target concept (or what the first model shows/explains). This is not a deficiency because models are used to generate knowledge relevant to the specific aspect of a phenomenon (Nersessian, 1995; Schwarz et al., 2009).

Data Generation

A case study does not claim any particular methods for data generation or data analysis. Any methods of data generation, "from testing to interviewing, can be used in a case study" (Merriam, 2009, p. 42). This study used qualitative data exclusively. A multilayered data corpus was generated through video and audio recording, think-aloud interviews, and artifacts. This expansive data set provided multiple entry points and perspectives on learners' experience building knowledge through multimodality embedded in modeling practices.

Video and Audio Recordings of Modeling Instruction

Classroom video and audio recordings were the most important part of the data since this study focused on the process of packing and unpacking the meaning and the switching taking place between everyday language and scientific language while learners engage in multimodal modeling experience. Capturing the discourse and interactions among learners generated insights into the research questions in this study.

One of the classes that I taught and collected data from was scheduled as primarily online synchronous due to the concerns about the ongoing pandemic of coronavirus disease (COVID-19). However, I scheduled some classes as outdoor in person on selected class days based on the weather. Given the class schedule and format, I implemented the modeling lesson and collected data during one of the outdoor in-person classes (see Figure 6 for the setting). The class met outside the building where learners usually had their classes.

Figure 6

The Outdoor Setting for the Modeling Lesson

Each individual received a package that included physical manipulatives and an instructional booklet. Learners had their materials, so they did not worry about touching the same materials that their groupmates also touched. Video cameras recorded the whole class teaching episodes in front of the classroom and the small group investigations and discussions that were conducted around different groups of learners who consented to participate in data collection. Learners who chose not to participate in data collection were not visible on the video camera. To ensure the quality of data, I had some assistance from the technology office at the university in recording audio and videos of the outdoor instruction. Another class that I collected data from was held in person in a regular classroom with the same precautions and data collection set-up detailed earlier.

Think Aloud Interviews

Interviews were included as part of the study to illuminate how learners used their model and modeling experience to process a science text as part of their knowledge-building process. These interviews specifically explored how packing and unpacking meanings and alternating between everyday language and scientific language could feature greater involvement between learners and the ideas in the text. This study expected that the knowledge-building experience through modeling would help learners establish semantic links among ideas and engage with the overall discursive flow in the text instead of distancing themselves from the text. The reason was that learners' experiences with multimodality embedded in modeling practices had the potential to make scientific texts appear more personal and less alienating. Interviews were expected to show how learners juxtaposed their informal linguistic resources (from both preexisting and subjectively new) with the more authoritative language of science.

Following the end of the formal instruction (on the same day or the day after the instruction), I interviewed learners who volunteered to take part in all aspects of data collection. Interview schedules were determined based on the availability of learners. Interviews were recorded in Zoom. Each participant was interviewed individually in a session that lasted approximately 45 minutes. During the interviews, learners were asked to read a textbook-style reading about glycolysis and interpret the ideas in the text by using their knowledge-building experience. They used annotations to process the text (highlighting the related parts of the text, labeling with their choice of modality, and explaining) and explained what their thoughts were as they annotated the text (think-aloud method). The screen-sharing feature of Zoom was useful for me to capture how learners annotated the text while thinking aloud. Think-aloud interviews encouraged learners to articulate their thoughts as they worked on a series of tasks so that (at least) some proportion of the information processing could be observable (Leighton, 2017). Speaking allowed learners' activity to become verbal so that the whole process could be recorded (Ericsson & Simon, 1993). Learners who declined to participate in data collection processed the reading as part of their ungraded assignment and they received written feedback on their text annotations.

I also asked follow-up questions in response to learners' annotations and the think-aloud process to understand the ways they processed the text (Roulston, 2010). The think-aloud interview protocol was developed and implemented in another study (e.g., Fackler et al., 2021). I used the same protocol (see Appendix D) with some modifications regarding the purpose of this study.

Artifacts

Artifacts included learner-constructed models (drawings), worksheets (glycolysis graphic novel and diagram), reflective essays on their understanding of models and modeling in science learning, and text annotations from interviews. Learners' ongoing, open-ended, social-to-personal knowledge-building artifacts in both product- and process-oriented aspects generated insight into how multimodality embedded in modeling could facilitate packing and unpacking meaning and shifts between everyday language and scientific language and influence learners' understanding of models and modeling in science learning.

Modeling Case and Commentary

A modeling case and a commentary (see Appendix C) were selected from a forthcoming book entitled Navigating the Challenges of Elementary Science Teaching and Learning: Using

Case-Based Pedagogy to Understand Dilemmas of Practice. The modeling case by Petersen (in press), entitled “Arts and Crafts” with a Side of Science, is about a model-based lesson that aims at developing students’ concepts of scientific models. At the end of the modeling project, in this case, students slip back into the idea that models are smaller versions of the real thing. The science teacher asks herself what she could have done differently so that students do not revert to their basic naïve understanding of models. The reason why this modeling case was used was that the author of the case is an inservice elementary science teacher and the case is an example of an implemented modeling lesson in a classroom setting. The commentary points out that it is important to explicitly teach what models are. It also encourages practicing and future teachers of science to reflect on their model-based instruction and the ways they address students’ naïve perceptions of developing a model in science classrooms. The commentary entitled The Good, the Bad, And the Misunderstood: Developing and Using Models was written by me. Preservice elementary science teachers read the modeling case and commentary before the formal modeling instruction and wrote a reflective essay about the case and commentary along with their experience learning with models and modeling after the instruction.

Data Management

The data corpus for this study was managed through NVivo 12 since the software facilitates the management and analysis of multiple data sources in multiple formats. For the sake of anonymity, all participants were assigned pseudonyms. It allowed me to connect participants’ responses from the different data sources. All digital files (audio and video files, interview transcripts, and scanned worksheets and artifacts) were saved in a password-protected computer, and only I have access to these documents. All files will be deleted at the conclusion and publication of this study.

Data Analysis

Adopting an interdisciplinary perspective to data analysis, I combined Multimodal Interaction Analysis (MIA), framed by Wilmes and Siry (2021), and the semantics dimension of Legitimation Code Theory (LCT), developed by Maton (2013), to examine how preservice teachers use a variety of semiotic resources for a range of meaning-making moments. MIA is used to carry out micro-analyses of the multimodal aspect of the engagement of preservice teachers in language and scientific practices, while LCT semantic density code is used to trace the shifts in meanings (shuttling between simpler meanings and complex, technical meanings packed in symbols, phrases, expressions, or gestures). The analyses looked at how multimodality employed by learners during the modeling instruction helped them make sense of the transfer of energy in glycolysis through the packing and unpacking the meaning and alternating between everyday language and scientific language.

MIA problematizes the language-centric view in science education by focusing on embodied aspects of learning (Wilmes & Siry, 2021). According to this analytical method, science learning is a process that unfolds both through and in interaction. MIA was influenced by the theoretical perspectives grounded in the work of Bakhtin (e.g., Bakhtin, 1986), and it highlights a dialogic view of human interaction (i.e., the nature of human interaction is a dialogue, and humans create individual meaning from interactions with text, media, and each other) in classroom contexts (Wilmes & Siry, 2021). In Bakhtin’s work, language is positioned as the most important aspect of communication. This view has dominated classroom-based educational research focusing on learners with different cultural and linguistic backgrounds. Wilmes and Siry (2021) aimed to combat this bias inherent in language-centric perspectives on teaching and research by building an analytical approach that foregrounds embodied utterance and engagement and emphasizes more equitable science learning opportunities for learners.

Wilmes and Siry's (2021) conceptualization of MIA takes a holistic approach to analysis. The unit of analysis represents individual actions. As an example of individual action from this study, student, Mary, placed her fingers on the magnet rings, pushed the third floating magnet down, and released her finger to let the third magnet go. This happened when she acted out the ATP energy story to make sense of how the ATP molecule gets energy, has energy, and releases energy. As this approach is grounded in embodied perspectives, it takes a more micro-interactional view than prior uses of MIA. This allows researchers to examine a variety of modalities employed by learners through interaction within the context of science learning.

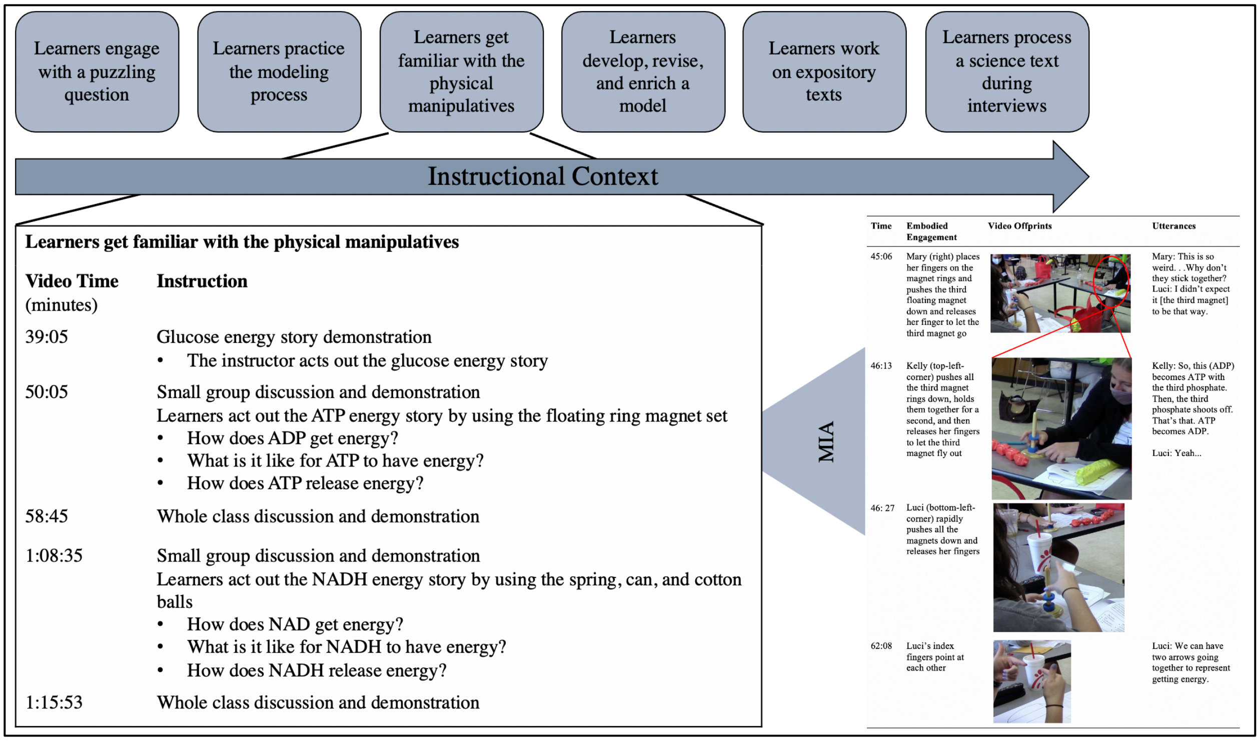
The analysis began with learners' embodied engagement in modeling, then coupled with their engagement in other modes of communication to reveal robust views of their knowledge-building experience. In particular, the analysis showed how explicitly foregrounding the embodied aspect and backgrounding the spoken aspect of learner engagement in modeling served to highlight the embodied ways in which learners engaged in packing and unpacking meaning and shifting between everyday language and scientific language. The data analysis included the following steps (Wilmes & Siry, 2021):

1. **Describing the context of the instruction.** The first step of analysis included analytic logs which presented a detailed overview of the context of the modeling instruction (Figure 7, left). The analytic log chronologically detailed events as they unfolded in real-time during the modeling instruction and interviews as reconstructed from a series of reviews of the audio and video-recorded instruction and interviews.

2. **Viewing videos with the audio muted.** The second step was watching each video with the audio muted. This step included documenting a variety of modes (gestures, gaze, and material interactions) employed by learners in their interaction with one another and thus viewing the videos multiple times. During this viewing, spoken language was backgrounded and de-emphasized. De-emphasizing spoken language did not mean that the importance of spoken language was taken away. Rather, it highlighted the other modalities that were as important in interaction as a spoken language by allowing researchers to break from a language-oriented view of learner engagement and interaction (Wilmes & Siry, 2021).

Figure 7

An Analytic Log (left) and Multimodal Transcript (right)



Learners get familiar with the physical manipulatives

Video Time (minutes)	**Instruction**
39:05	Glucose energy story demonstration • The instructor acts out the glucose energy story
50:05	Small group discussion and demonstration Learners act out the ATP energy story by using the floating ring magnet set • How does ADP get energy? • What is it like for ATP to have energy? • How does ATP release energy?
58:45	Whole class discussion and demonstration
1:08:35	Small group discussion and demonstration Learners act out the NADH energy story by using the spring, can, and cotton balls • How does NAD get energy? • What is it like for NADH to have energy? • How does NADH release energy?
1:15:53	Whole class discussion and demonstration

Time	Embodied Engagement	Video Offprints	Utterances
45:06	Mary (right) places her fingers on the magnet rings and pushes the third floating magnet down and releases her finger to let the third magnet go		Mary: This is so weird. . .Why don't they stick together? Luci: I didn't expect it [the third magnet] to be that way.
46:13	Kelly (top-left-corner) pushes all the third magnet rings down, holds them together for a second, and then releases her fingers to let the third magnet fly out		Kelly: So, this (ADP) becomes ATP with the third phosphate. Then, the third phosphate shoots off. That's that. ATP becomes ADP. Luci: Yeah...
46: 27	Luci (bottom-left-corner) rapidly pushes all the magnets down and releases her fingers		
62:08	Luci's index fingers point at each other		Luci: We can have two arrows going together to represent getting energy.

3. **Constructing multimodal transcripts.** The next step was the construction of multimodal transcripts (see Table 5 or Figure 7, right). Traditionally, spoken language is the mode that is transcribed first for two reasons: its high information value and educational training that places great importance on the mode of language—what a learner is saying vs. what the learner is expressing in other modes (Norris, 2004). However, while analyzing the data in this study, the embodied aspects of learner engagement were foregrounded. To do so, I watched each video with the audio muted. The purpose was to document a variety of modes (gestures, gaze, and material interactions) employed by learners in their interaction with one another. During this process, spoken language was backgrounded and de-emphasized. For instance, viewing each video with the audio muted helped me focus on Taylor's interaction with the manipulatives. As presented in Figure 8, Taylor combined different components of the manipulatives to see how they can be acted out together to show how energy-carrying molecules get, have, and release energy. When I asked learners to finish up the ATP energy story and act out the NADH energy story, Taylor in Group 1A squeezed the spring and put the spring and the cotton balls in the can. Then, she released the top and saw the spring and the cotton balls fly away. She repeated this several times. Next, she stopped and fixed her gaze on the ATP manipulative, the magnet set. Taylor then grabbed the magnet set, squeezed the spring through the base (Panels 1 and 2 in Figure 8), held the spring just like she held the can representing the NADH (Panel 3 in Figure 8), and released the spring (Panels 4, 5, and 6 in Figure 8). This time the spring flew away further than the third magnet did. No verbal exchanges were involved at this moment. The embodied aspect of her

> interaction with the material showed that she was able to apply what she learned from and about the ATP manipulative to the NADH manipulative. This experience might provide her with an opportunity to multiply meaning across multiple manipulatives showing how molecules get, have, and release energy.

Since all transcription is selective and theory-driven (Erickson, 2017), the multimodal transcripts in this study emphasized certain aspects of interaction (e.g., packing and unpacking meaning or switching between everyday language and scientific language) over others by using diverse approaches to transcription. For instance, playscript-based approaches to transcription overlook the representation of what students are doing while the instructor is speaking (Erickson, 2017). As illustrated in Figure 8, I adopted a horizontal approach to transcription (Condon, 2004) to reveal the embodied aspects of knowledge building by learners because knowledge building

Table 5

An Illustrative Example of a Multimodal Transcript Excerpt

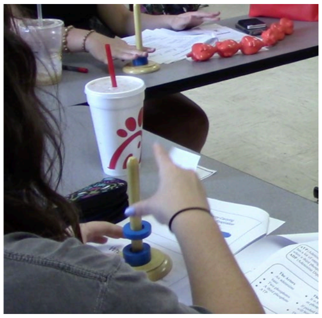
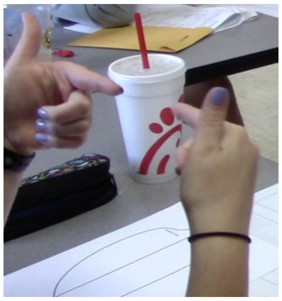
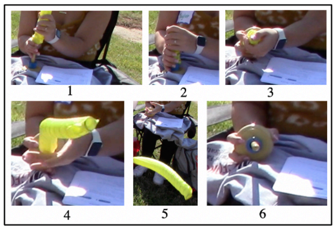
Time	Embodied Engagement	Video Offprints	Utterances
45:06	Mary (right) places her fingers on the magnet rings and pushes the third floating magnet down and releases her finger to let the third magnet go		Mary: This is so weird. . .Why don't they stick together? Luci: I didn't expect it [the third magnet] to be that way.
46:13	Edna (top left corner) pushes all the third magnet rings down, holds them together for a second, and then releases her fingers to let the third magnet fly out		Edna: So, this (ADP) becomes ATP with the third phosphate. Then, the third phosphate shoots off. That's that. ATP becomes ADP. Luci: Yeah...
46: 27	Luci (bottom-left-corner) rapidly pushes all the magnets down and releases her fingers		
62:08	Luci's index fingers point at each other		Luci: We can have two arrows going together to represent getting energy.

Figure 8

An Illustrative Example of a Horizontal Approach to Transcription

What the instructor says:	What the learner does:	What the learner says:	What the other learners say/do:
"Okay, finish up the ATP energy story. Now, we will act out the NAD story. Get your manipulatives from your bag." →	 Taylor fixes her gaze at the ATP manipulative, the magnet set. She, then grabs the magnet set, squeezes the spring through the base (Panel 1 and 2), holds the spring just like she holds the can representing the NADH (Panel 3), and releases the spring (Panel 4, 5, and 6). She observes that the spring flies away further than the third magnet does. →	No verbal exchanges →	No verbal exchanges or embodied actions Only her group members watch her combining the two manipulatives, ATP and NADH

4. **Selecting the analytical focus and sampling video data.** From the previous step, the construction of multimodal transcripts, possible analytical foci emerged. In this case, the analytical foci were relative to particular learners, particular forms of interactions among learners, and between learners and instructional materials (i.e., physical manipulatives, a diagram, text, and drawing). Since it is not feasible to analyze every second of the video recordings (a total of 1413 minutes of data in this study) for multimodal transcription (Jewitt, 2006), 820 minutes of video data were selected based on the following criterion: Video data revealed moments when the meaning might be reconstructed using multimodal resources (when knowledge was represented, articulated, exchanged, interpreted, and even reproduced by learners using multiple modes).
5. **Layering on other modes of communication.** The next step of analysis involved viewing the videos with the audio on. This step helped interpret the non-verbal modes

of communication. For instance, the meaning of a hand gesture may not be possible to interpret without further enhancement from other modes such as verbalization. The reasoning for layering spoken language during this step of the analysis was to purposely offset the use of spoken language as the guiding principle for the analysis of knowledge building. Viewing videos with the audio off and layering on spoken language was conducted over multiple rounds of viewing the videos. By doing so, I refined and reduced the data and narrowed the focus to packing and unpacking meaning within and across modalities. This allowed for the analysis to be aligned with the theoretical framework of the study that focuses on constant shifts in meaning in knowledge building (Maton, 2013).

6. **Moving from interactions to episodes/categories.** As the theoretical framework indicates, knowledge is socially constructed by learners using multimodal resources in science classrooms. This is also considered (science classroom) discourse (Kress & Van Leeuwen, 2001). Discourse can be identified through interactions (Britsch, 2009). Interactions, in this analysis, referred to events that occurred between learners, between learners and me, and between learners and learning materials to build knowledge in this study. A series of sequenced interactions created codes, and these codes led to episodes/categories. Tables 6, 7, and 8 present some illustrative examples of a series of interactions, codes, and episodes/categories for each research question.

Table 6

An Illustrative Example of a Series of Interactions, Codes, and Episodes Regarding RQ1

Excerpt From the Data	Interaction	Code(s)	Episode
Melissa reads the following: "Once together, NADH is in a high-energy state". She then goes on to say, "So I would say that NADH has energy. It'd be having. It's like sizzling. It's Mmmm! for us".	Reading aloud the science text	Interpretation Rearticulation	Generating and Employing Different Modalities
Laura explains her group's model: "It is basically showing that you have to use force to add it in" <she pushes the palm of her right hand to the front and then pulls it back>. "Like they don't click together easily. You have to push them hard" <she repeats the same gesture>.	Explaining the drawing	Representation Rearticulation	Generating and Employing Different Modalities
Diane: "So, this is saying that glucose is split. It's releasing energy" <her hands show small explosions by slowly separating her touching fingers and hands> "Um, so it's releasing energy for us [referring to her group's model] that is a boom because of the big explosion at the end".	Reading aloud the science text	Expression Explanation	Unpacking Meaning Through Modalities

Table 7

An Illustrative Example of a Series of Interactions, Codes, and Descriptions Regarding RQ2

Excerpt From the Data	Interaction	Code	Description
“These [parentheses] represent the stored energy in the molecule”.	Explaining the drawing that represents the molecule having energy	Scientific language	Introducing and using expressions, phrases, terms, and concepts that come from written texts by professional scholars or textbook writers
“…that is part of the reason we made our sound, Ahhh, because it was almost like the molecules are like screaming because they’re being kind of whisked away from each other”.	Explaining what releasing energy means	Everyday language	Introducing and using expressions, phrases, terms, and concepts in familiar contexts such as their own everyday lives and direct experiences

Table 8

An Illustrative Example of a Series of Interactions, Codes, and Categories Regarding RQ3

Excerpt From the Data	Interaction	Code	Category
“…models can be constructed by the students, integrated with different modes like kinesthetic movements and verbal sounds”.	Reflecting on the modeling case/commentary and practice itself	Noticing different modes in models/modeling	Models As Multimodal Tools
“We did stand up and act out our model using hands and sound effects. This threw the whole thing together and reinforced our conceptual ideas…”	Reflecting on the modeling experience	Appreciating different modes in models/modeling	Models As Multimodal Tools
“I definitely just thought of models as smaller versions of the real thing!”	Reflecting on the modeling case/commentary and practice itself	Noticing the naïve perception of models being copies of real phenomena	Models Beyond Copies of Reality

Through an inductive approach, I closely examined and coded the interactions between learners (e.g., classroom instruction), between learners and me (e.g., classroom instruction and interviews), and between learners and learning materials (e.g., classroom instruction and interviews) to answer the first and second question. After developing the episodes in response to the first research question, I re-analyzed each episode using the semantic density code of LCT to show the different trajectories through which meanings were packed and unpacked through diverse modalities. I conceptualize observed shifts in meanings in terms of the increase and decrease in semantic density. Focusing on multiple meaning-making moments with multiple modes and modalities, I examined how the development and use of diverse semiotic resources could help students increase or decrease the semantic density of the meanings they made while they pack and unpack these meanings. For instance, when a student/group draws a model to represent molecules having energy, their drawing is imbued with meaning (e.g., two circles [molecules] are attached along with a parenthesis on each side), which increases the semantic density. This is an example of packing meanings. In addition, Figure 9 shows how Mary gradually packs meanings by using physical manipulatives, verbal expressions, and drawings throughout her experience developing a model to represent how the energy-carrying molecules transfer energy. Specifically, Figure 9 first shows Mary interacting with the manipulative for ATP to figure out what it looks like for ATP to get energy. Then, she begins to discuss what happens with her group and asks herself and them, “why don’t they stick together?”, which represents the idea that the molecular entities in ATP need to attach one another to form ATP from AMP or ADP. Her idea surfaces again when she explains her drawing for getting energy by saying, “while they are getting energy, they are being pushed together by the two arrows [see her drawing for getting energy on the right]”. When a student/group explains their drawing or part of it (e.g., two parentheses in the drawing for having energy), they unpack the meaning by elaborating on what these two parentheses represent, "it [molecule] is shaking", which causes the semantic density to decrease. Table 9 presents the translation device that was used to code for semantic density in this study.

Table 9

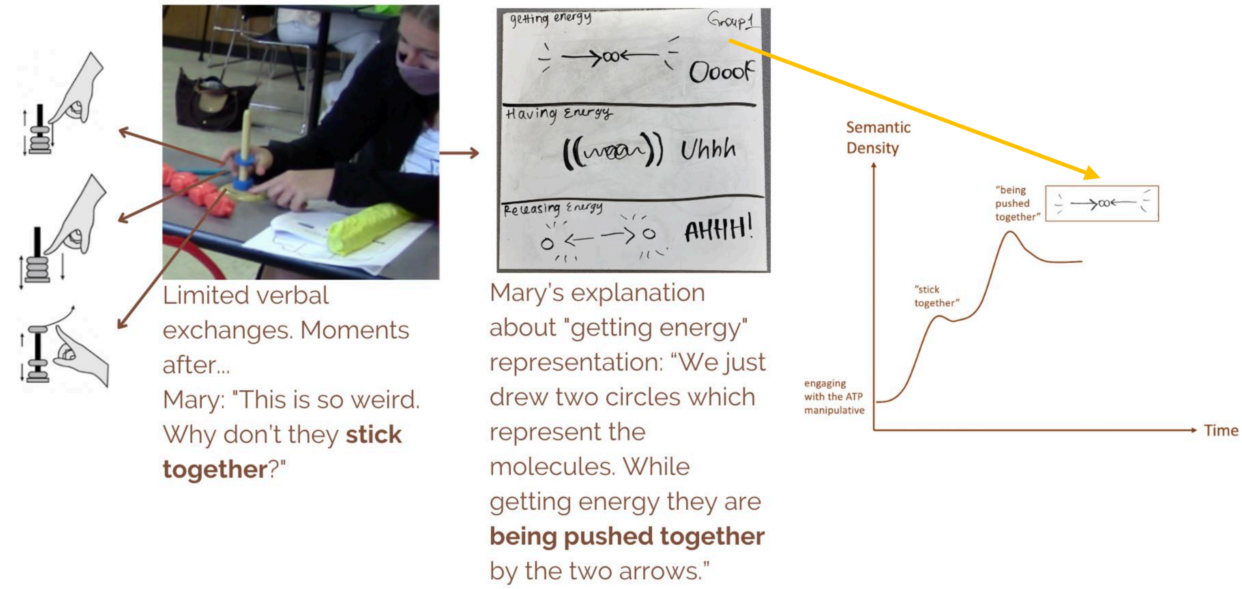
Description of Coding with Examples for Semantic Density Regarding RQ1 and RQ2

Semantic Density	Description of coded content	Example of student responses
Increasing semantic density /Packing meanings	Students develop and use a symbol, phrase, expression, gesture, gaze, drawing, and other semiotic resources that are imbued with meanings	"We can draw a squiggly line to represent the vibrations [the molecule having energy] …then draw some lines outside [the molecule] to show the force"
	Students add complexity to everyday words and phrases	"It [the one molecule breaking off from the other in releasing] shows that it breaks off from the chain [molecule]" (the word "chain" no longer means a series of connected metal rings, and it represents a molecule in this case)
	Students make connections among different scientific ideas	"For getting, this [two circles attached in her drawing] is what is already there. This [the third circle] moves this way, but there is that resistance"
Decreasing semantic density /Unpacking meanings	Students simplify and contextualize meanings by using different semiotic resources	"In glycolysis, glucose is split into two smaller carbon molecules [the student reading the original sentence in the text]. So, this is saying that glucose is split. So, it's releasing energy <her hands show small explosions by slowly separating her touching fingers and hands>"

Note. [ ] added for clarification purposes. < > indicates gestures used by students.

Figure 9

Mary Packing Meanings Through Her Engagement with Physical Manipulatives, Verbal Expressions, and Drawings



Limited verbal exchanges. Moments after...
Mary: "This is so weird. Why don't they **stick together**?"

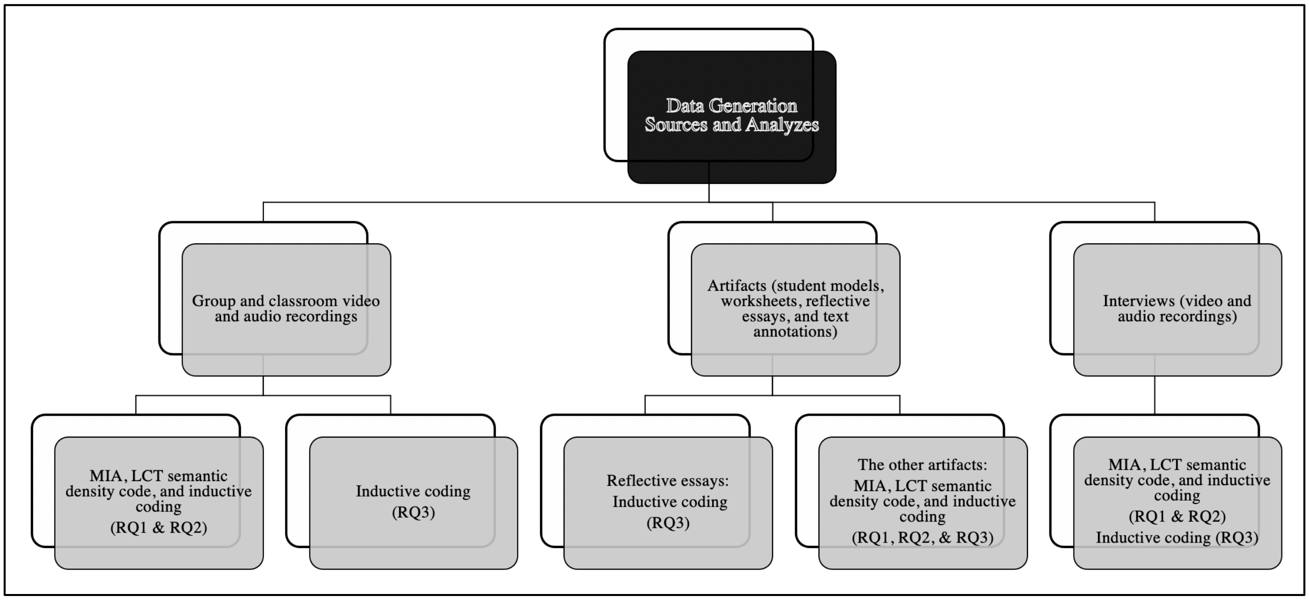
Mary's explanation about "getting energy" representation: "We just drew two circles which represent the molecules. While getting energy they are **being pushed together** by the two arrows."

Following the similar steps detailed above, I re-analyzed each interaction (coded as scientific language vs. everyday language) using the semantic density code of LCT to examine in what ways multimodal modeling practices play a role for students in their switching between everyday language and scientific language. For instance, when students add new complexity to everyday words and phrases, the semantic density increases (see Table 9 for the description of coded content). As a specific example from the data set, Laura talks about her group model (see Figure 23 in the Findings section for the model) representing molecules releasing energy when asked to explain what one molecule breaking off from the other in releasing energy represents and shares the following: "It shows that it breaks off from the chain [molecule]". She uses the word "chain" instead of the molecule and adds new complexity to an everyday word, increasing the semantic density of the word. This shift between scientific language and everyday language is explained by the semantic density and shows that semantic waving occurs in all classroom discourse, and it means that there can also be packed meaning (high semantic density) in everyday discourse and not just in disciplinary discourse.

To answer the third research question, I used an inductive approach and closely examined and coded the learners' reflective essays describing their experience developing a model and how their experience might change what they think about models and modeling in knowledge building. Table 8 presents the interactions, codes, and categories that I developed based on the analysis. Figure 10 presents the data generation sources and summarizes how they are used in the analyses.

Figure 10

The Data Sources and How They Are Used in The Analyses



To ensure the credibility of the analysis, a graduate student, and a postdoctoral researcher with a background in science education and qualitative methodologies were consulted to check the coding process and its relation to the research questions. The coding process was revised based on the exchange of suggestions and negotiations. With this elaboration of the steps in the data analysis, in the following chapter, I presented episodes/categories that emerged from a comparison (Patton, 2015) of aspects of packing and unpacking meaning, switching between everyday language and scientific language, and understanding of models and modeling in knowledge building in science across the groups and participants.

Data Quality

Validity

Internal validity was addressed by a data source triangulation including video and audio recordings of instruction, think aloud interviews, and artifacts such as learner-constructed models, worksheets, and reflective essays (Stake, 1995). In addition, I provided a disclosure of my possible bias through my positionality statement (Merriam, 1998). External validity was addressed by producing a thick description of interconnections among data, its sources, its meaning, and its relation to theory (Merriam, 1998). A thick description in this study included arguments and discussions around the sources of data, how the data interconnect, how each extract means what it means, and the relationship with the theory (Holliday, 2007).

Reliability

Following advice from Miles and Huberman (1994), I conducted a coding check on the video and audio transcripts of instruction and the interviews to refine the working definitions and test the reliability of the coding scheme. To do so, the data set was independently coded by two more researchers (a senior Ph.D. student in science education and a post-doc researcher in elementary and early childhood education with expertise in qualitative methodologies). Then, the coded data set was reviewed together to evaluate inconsistencies in respective interpretations of the codes.

Limitations

This study contains some limitations. First, I accept that in this qualitative research and the interviews with the participants in this study, the data are partial, incomplete, and always in the process of re-telling and re-constructing. Second, as I reported earlier, the level of experience that my participants had with modeling practices in science learning was very limited. A study with preservice teachers who have experience using and developing models might paint a very different picture. Third, the findings might be a result of the specific modeling instruction (inductive modeling) introduced in this study. Other ways of developing a model (e.g., computational modeling) could result in a different understanding of models and modeling in knowledge building in science.

CHAPTER 4

FINDINGS

Research Question 1: Packing and Unpacking Meaning in Knowledge Building

This section reports the findings of the first research question: How did multimodal modeling practices facilitate packing and unpacking meaning in knowledge building in science? The analysis of multimodal aspects of the practice of modeling within and across the groups allowed me to characterize the ways learners packed and unpacked meaning while building knowledge. Three episodes show three important processes that helped learners pack and unpack meanings while learning about the transfer of energy in glycolysis by using multimodal modeling practices: engaging with materials to initiate packing meaning, generating and employing different modalities, and unpacking meaning through modalities. Episode 1 shows how the process of packing meanings can be initiated and unfolded through embodied interactions between learners and materials. Episode 2 presents how learners further packed meaning into written, drawn, and verbal expressions as well as gesticulations as part of their modeling (the modeling process or the modeling product) and how they used these modalities that were imbued with meaning to engage with the learning materials (i.e., science texts). Episode 3 highlights how learners unpack meaning by using their self-constructed modalities. This episode presents different ways of unpacking such as unpacking the meanings of specific modalities to interpret ideas and concepts presented in the text, unpacking ideas and concepts presented in the text by referring to specific modalities, unpacking ideas and concepts in the text by generating instantaneous expressions that were not part of (but influenced by) the modeling experience, and unpacking the meanings packed into specific modalities during the model development. Some episodes highlight a certain aspect of modeling (e.g., the modeling practice activity or using physical manipulatives), while others focus on the modeling process, the modeling product, and the use of models. For each episode, I elaborate on findings and present illustrative excerpts from the analysis. As the excerpts that support each episode are multiple, I present representative excerpts to elaborate on each episode in the sections that follow. While selecting particular examples for this section, I aimed to illustrate the variations in each episode or category. For instance, to unpack Episode 2: Generating and Employing Different Modalities in response to the first question, I present examples that came from different points in the modeling instruction (e.g., developing an initial model, revising and enriching the model, acting out the model or using the model to process a text) and are facilitated by the use of different modalities (e.g., drawings, verbal expressions, written explanations, sound words or gestures). < > indicates embodied actions. Statements in brackets were added for clarification purposes.

Episode 1: Engaging with Materials to Initiate Packing Meaning

Learners were first engaged with each energy-carrying molecule, its parts, and a narrative on how the molecule can assemble, remain assembled, or break into constituents by using physical manipulatives. They observed the molecular configurations (metaphorically assembling and disassembling the parts of the molecules) of getting, having, or releasing energy. The idea of getting, having, or releasing energy became the underlying structure that learners developed a model of.

In this episode, the engagement was mostly multimodal and embodied without any significant verbal exchanges. For instance, without speaking to their groupmates, learners first picked up the ATP manipulative and gazed at the magnets. Then, they figured out how the magnets should be placed on the base (i.e., they had to figure out whether the magnets should repel each other or snap together). Mary from Group 1B, for instance, placed her fingers over the magnets, pushed only the third magnet down (the other two were snapped together), released her fingers, and observed how the third magnet flew off, with her gaze fixed on the magnet set. She repeated this action several times. If Mary's interaction with the materials were framed through only verbal exchanges, the process of exploring how each manipulative represents how molecules get, have, and release energy would be easily overlooked.

Moments after Mary interacted with the manipulative, she asked her partners, "This is so weird. Why don't they stick together?" At this moment, she tried to see how ATP gets energy by repeatedly pushing the third magnet down. Her engagement with the manipulative provided her with further insights into how energy-carrying molecules getting, having, and releasing energy can be represented through a model. For instance, her phrase "stick together" became an idea to talk about an energy-carrying molecule getting energy; it was represented in her group's model as molecules "being pushed together" (see Figure 11). When I asked Mary to walk me through the getting energy phase in her group's model, she went on to say, "We just drew two circles which represent the molecules [three energy-carrying molecules]. For getting energy, they are being pushed together by the two arrows".

Figure 11

A Model for the Transfer of Energy Constructed by Group 1B

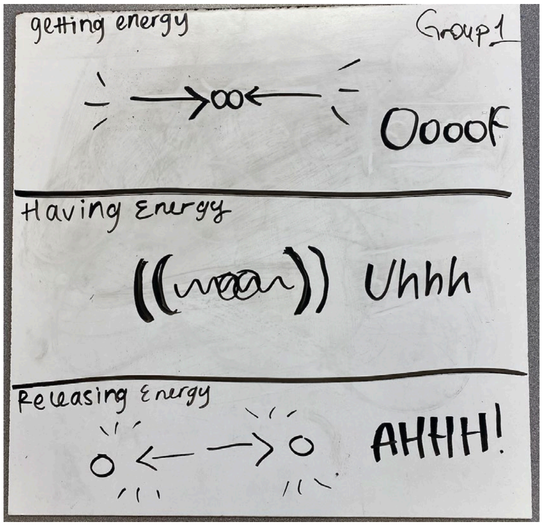
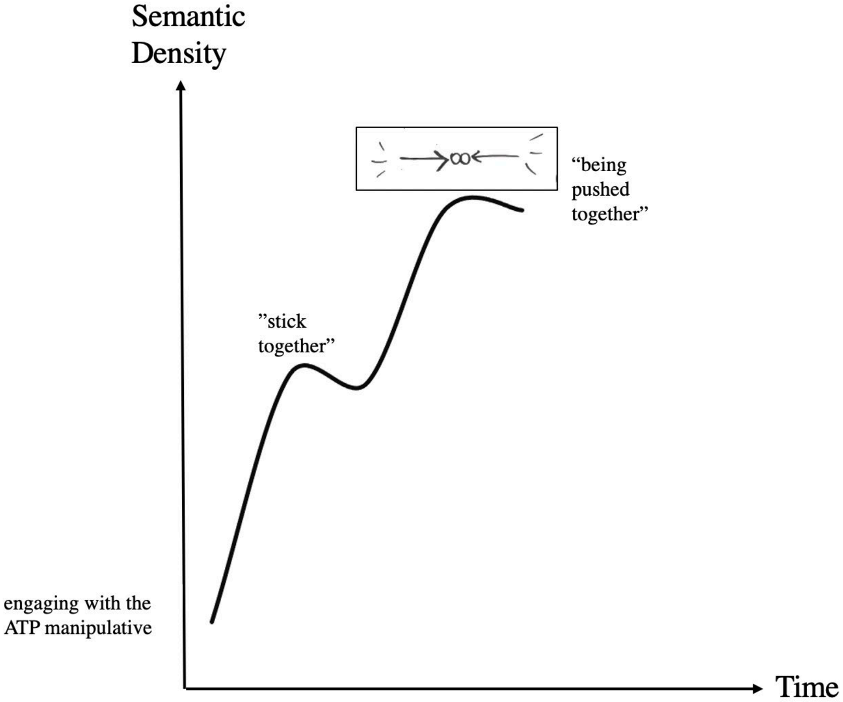


Figure 12

The Semantic Profile of Mary Packing Meaning Through Engaging with Materials in Modeling



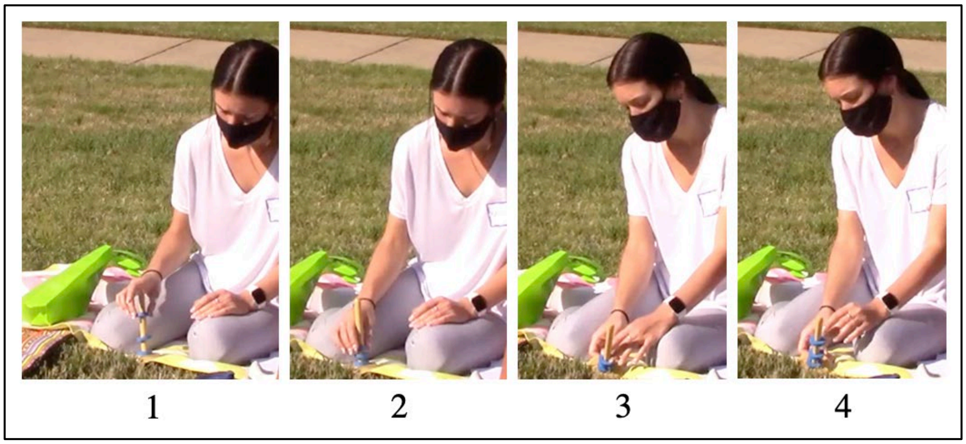
As depicted in Figure 12, the semantic profile of packing meaning through engaging with physical manipulatives at the beginning of the practice of modeling featured a series of upward semantic shifts (increasing semantic density): from simpler, concrete experiences and meanings (including, but not limited to everyday phrases and words) towards condensed, decontextualized ideas, phrases, symbols, and expressions. Representing Mary's experience packing meaning, this profile showed how Mary repeatedly packed her experience with materials along with the ideas into phrases and symbols in her drawing. For instance, she first used her concrete and haptic experience engaging with the ATP manipulative to understand how a third phosphate can be attached to ADP and how ADP turns into ATP, which metaphorically refers to the process of getting energy. This led Mary to pack her direct interaction with materials into a phrase, "stick together", when she described what she observed and discussed with her group members. She preserved this phrase along with its meaning packed in this phrase and further packed this meaning ("stick together") into a new modality (a drawing) when she drew a model to represent how an energy-carrying molecule can get energy later in the process of modeling (see "getting energy" in Figure 11). Her drawing included three main symbols (i.e., arrows, circles, and short lines) that were imbued with meaning. When I asked her about the getting energy phase, she further packed the meaning of the drawing into another modality by verbally introducing the phrase "being pushed together". Showing movements upwards, this profile showed that rich multimodal meanings emerged through her embodied interactions with materials at the beginning of the modeling practice and were carried to the later steps in modeling instruction, increasing the semantic density repeatedly.

As another example of engaging with materials without significant verbal exchanges, Melissa appeared to figure out how the ATP manipulative represents getting, having, and releasing energy. Her engagement with the manipulative helped her experience how ADP gets energy and becomes ATP, what happens when ATP has energy, and how ATP releases energy.

In her first attempt to show getting, having, and releasing energy, Melissa grabbed the three magnets and placed them onto the base. Her gaze fixed on the magnet set, she pushed the magnets down (Panels 1 & 2 in Figure 13), held them together by pressing her index and middle finger together (Panel 3 in Figure 13), released her fingers, and let the magnets float (Panel 4 in Figure 13).

Figure 13

Melissa's First Attempt to Show Getting, Having and Releasing Energy with ATP Manipulative

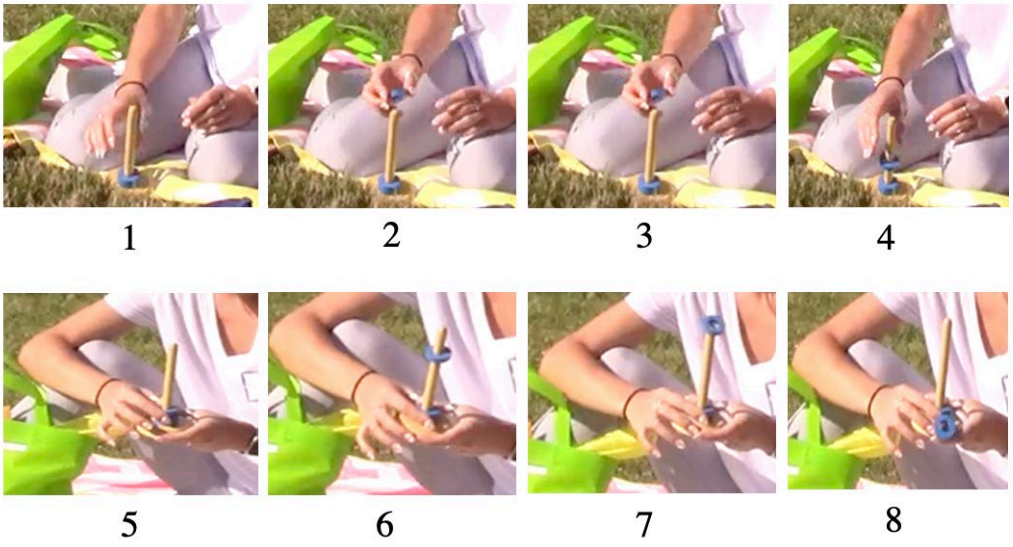


Melissa's first engagement with the manipulative showed her that magnets repel each other rather than representing getting, having, and releasing energy. Observing her classmates and reading the ATP energy story one more time, Melissa noticed that she should show getting energy by pushing the third magnet down and attaching it to the other two magnets that were already attached and the base. She modified the way she placed the magnets on the base. In her second attempt, Melissa first placed two magnets snapped together on the base (Panel 1 in Figure 14). She then carefully placed the third magnet on the other two magnets (Panels 2 & 3 in Figure 14) and observed how the third magnet repelled the other two magnets (Panel 4 in Figure 14). Next, Melissa pushed the floating third magnet down with her thumb and index finger (Panel 5 in Figure 14) and released her fingers (Panel 6 in Figure 14). She then looked at the third magnet flying off and landing on the ground (Panels 7 & 8 in Figure 14). Melissa repeatedly pushed the third magnet down and released her fingers and saw the third magnet flying away. No verbal exchanges took place during Melissa's interaction with the ATP manipulative. However, she had the haptic experience of applying or releasing a force to change the energy state of the ATP while acting out the ATP energy story. This was evident in her reflective essay on her modeling experience when she wrote,

> "You could feel the force of pushing the opposite poles of the magnets together and you could see the explosion of energy as the magnets flew apart from each other, I better understood how the force used to add the third phosphate molecule in ATP created an energy that was ready to be released".

Figure 14

Melissa's Second Attempt to Show Getting, Having and Releasing Energy with ATP Manipulative



Interacting with the ATP manipulative provided Melissa with an alternative way in which she could build knowledge about how ADP gets energy, what happens when ATP has energy, and how ATP releases energy. By doing so, Melissa, for instance, began to understand what it means for energy-carrying molecules to need some force applied to their molecular entities so that they can be pushed together. She started packing her ideas about getting, having, and releasing energy through her experience with physical manipulatives. These initial ideas manifested themselves in her group's model development later in the instruction. For instance, when Melissa was asked to explain her group model (see Figure 15), she verbalized, "we wanted to represent general objects being pushed together (getting energy), radiating (having energy), and pulling apart (releasing energy)". She, for instance, experienced how it feels to push molecules together when she interacted with the ATP manipulative. Foregrounding her embodied interactions with the manipulatives in the analysis highlighted her internalized way of building knowledge. To perform an analysis that looks for any verbal exchanges to describe and examine Melissa's knowledge-building experience would underestimate how powerful a haptic experience could be.

Figure 15

Melissa's Group Model (Initial)

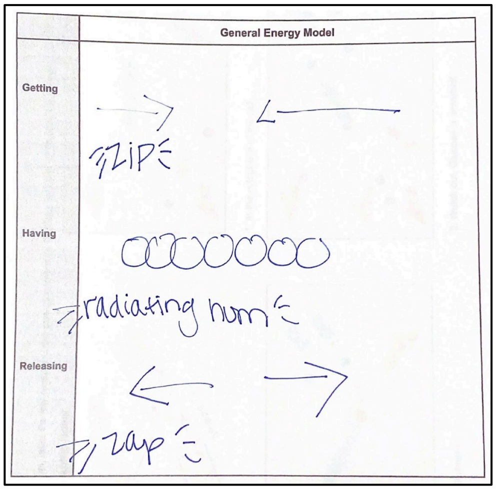
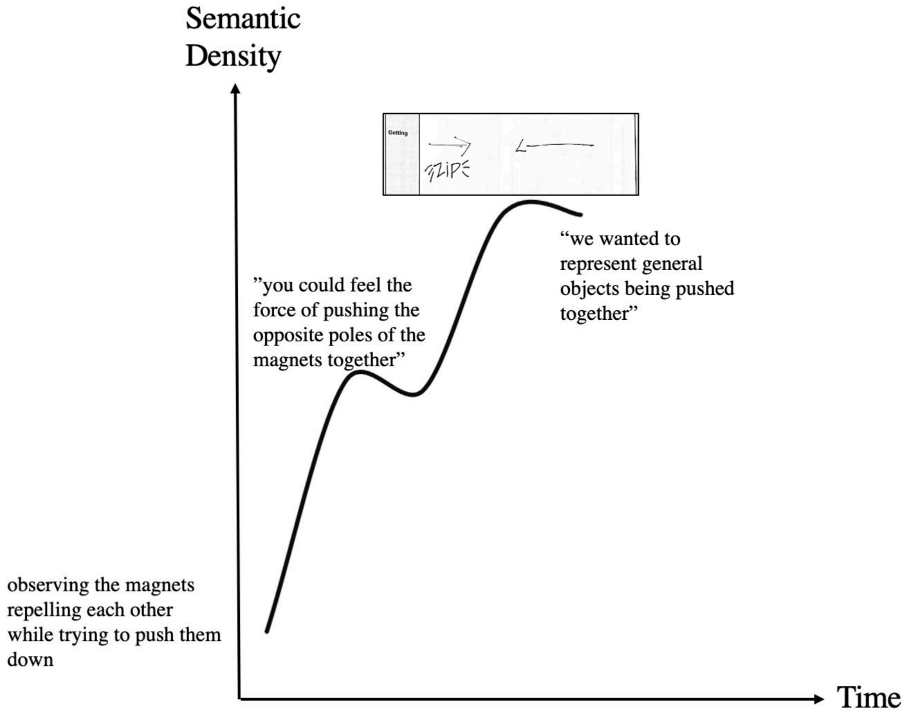


Figure 16

The Semantic Profile of Melissa Packing Meaning Through Engaging with Materials in Modeling

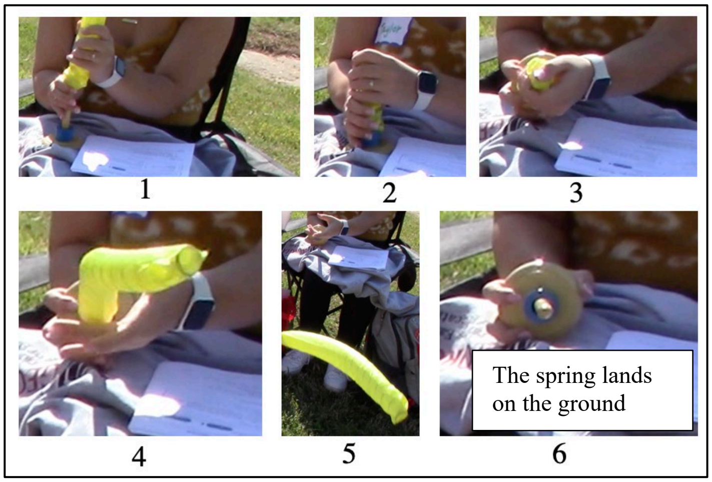


Representing how engaging with materials initiated the process of packing meanings, Melissa's semantic profile (see Figure 16) also showed how she repeatedly packed her direct experience with materials along with the ideas into phrases, expressions, and symbols in her drawing. For instance, Melissa first observed how the magnets representing the phosphates in ATP repel each other while she pushed them down with her fingers (see Figure 13). Then, she moved from this concrete experience/observation to a more complex idea "force" when she reflected on her experience modeling and wrote, "You could feel the force of pushing the opposite poles of the magnets together". She increased the semantic density of her concrete interaction with materials and packed meanings into the term "force". When she drew a model of getting energy, she further packed meanings into two main symbols, two arrows, and the sound word “Zip” (see Figure 15), by further condensing, and decontextualizing the idea of force. After she and her group were done with their final model, I asked Melissa about the getting energy phase in the model. She then moved from her symbols representing the force to the phrase “being pushed together”. These upward movements portrayed that Melissa progressively strengthened semantic density by packing up the various interactions, experiences, and ideas.

In another instance, when I asked learners to finish up the ATP energy story and act out the NADH energy story, Taylor in Group 1A squeezed the spring and put the spring and the cotton balls in the can. Then, she released the top and saw the spring and the cotton balls fly away. She repeated this several times. Next, she stopped and fixed her gaze on the ATP manipulative, the magnet set. Taylor then grabbed the magnet set, squeezed the spring through the base (Panels 1 and 2 in Figure 17), held the spring just like she held the can representing the NADH (Panel 3 in Figure 17), and released the spring (Panels 4, 5, and 6 in Figure 17). This time the spring flew away further than the third magnet did. No verbal exchanges were involved at this moment. The snapshots of the video capturing Taylor’s interaction with the manipulatives are presented in Figure 17.

Figure 17

Combining Two Manipulatives to Show a Molecule Getting, Having and Releasing Energy



Taylor applied what she learned from and about the ATP manipulative to the NADH manipulative. This experience might provide her with an opportunity to multiply meaning across multiple manipulatives showing how molecules get, have, and release energy. Moments later, when I asked Taylor to explain the gestures that her partners and she added to their model, she went on to say, "We used our fingers. When they [the energy-carrying molecules] get energy, they start like crawling <she holds her hands up in the air, and her fingertips meet in the middle> and then you are getting them together <her fingertips and palms touch each other), they have energy. Then, releasing <her hands move to the opposite ways and fingers fly away>". Taylor used her experience combining the ATP and NADH manipulatives to generate gestures to explain her groups model, such as crawling fingers referring to the way she slowly squeezed the spring into the can and through the magnet base by using her fingers or flying fingers indicating that the spring (or the magnet) flies away when it is released.

In Episode 1, learners initiated the process of packing meaning by using their immediate experiences with the materials, which involved little to no verbal exchanges at the beginning, to build generalizable relatively new entities that can be functional further in their knowledge-building experience. Episode 1 showed that knowledge building in science classrooms can be initiated and unfold through embodied interactions between learners and materials. Learners' engagement with the physical manipulatives paved the way for them to condense ideas and meanings into the modalities that they generated and used in this study.

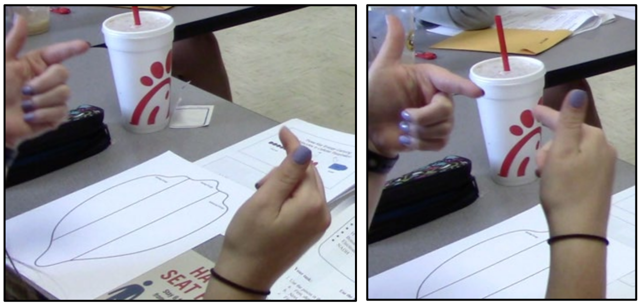
Episode 2: Generating and Employing Different Modalities

This episode shows that learners further packed meaning into written, drawn, and verbal expressions as well as gesticulations to talk about the transfer of energy. Building on their experiences with the physical manipulatives, learners continued to condense the meaning they encountered by deploying a variety of modalities. Learners developed their models and elaborated on them by representing meaning through their emergent gestures, labels, and sound words. This provided multiple avenues for them to participate in science learning by backgrounding scientific language. Consider the following dialogue among the members of Group 1B during their initial model development.

Mary: How should we do this?

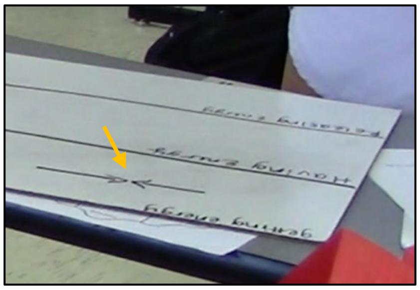
Edna: We can do like three squares.

Luci: We can have two arrows going together to represent getting energy <her index fingers point at each other and come close together slowly>.



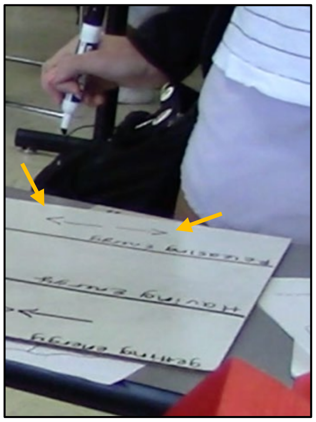
Mary: Like that? [She draws two arrows pointing at each other]

Edna and Luci: Yep.

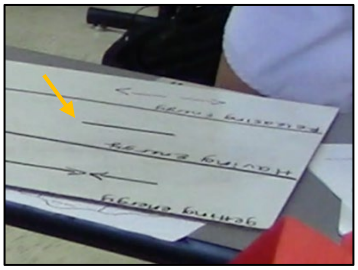


Edna: And for releasing, at least one arrow could go the opposite way <she gestures to Mary as shown on the right>.

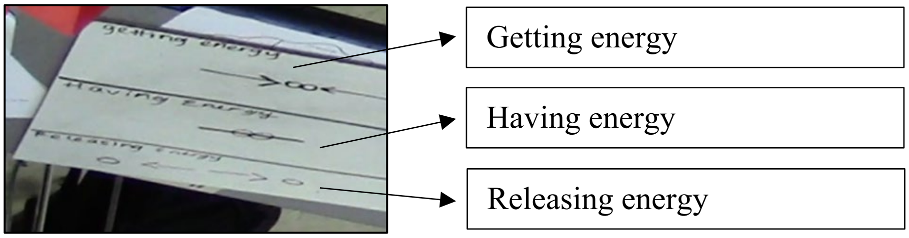
Mary drew two arrows going in opposite directions as shown on the right.



Mary: For having energy, it is just like a straight line, no arrows. It is kinda just sitting there.

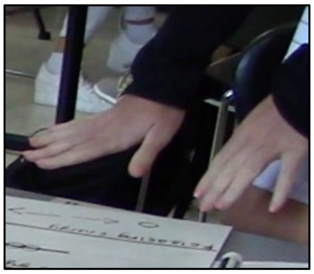


Mary, Edna, and Luci used their gestures, drawings, and verbal expressions as a central component of their thinking about molecules getting, having, and releasing energy. First, the idea of molecules getting energy was packed into Luci's hand gesture <her index fingers pointing at each other and coming close slowly> to depict how the atoms or molecular entities of the energy-carrying molecules are pushed together when the molecules get energy. Next, being influenced by Luci's gesture, Edna generated her gesture to represent what it means for an energy-carrying molecule to release energy. She condensed the idea that the atoms or molecular entities of an energy-carrying molecule are detached from the molecule by breaking one or more high-energy bonds into her gesture. This was evident in her verbalization when she said, "and for releasing, at least one arrow could go the opposite way". This detachment-yielding energy was represented by two arrows going in different directions in their model. Last, Mary condensed the idea of molecules having energy into a straight line, and then verbalized, "for having energy, it is just like a straight line, no arrows. It is kinda just sitting there". Without any verbal communication, Mary then drew two circles between the arrows for getting energy, two circles in the middle of the straight line for having energy, and one circle at each end of the arrows for releasing energy. She felt a need to represent the energy-carrying molecules by two random circles in their model as well.



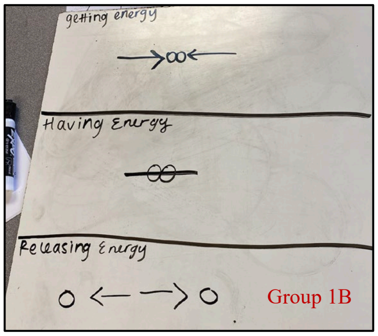
Learners continued to generate, revise, and enrich their semantic expressions (i.e., written, verbal, pictorial, and embodied) during the model share-out session that aimed to bring the ideas being worked on in small groups to the whole class. For instance, when Mary introduced her group's model to the whole class, she shared the following.

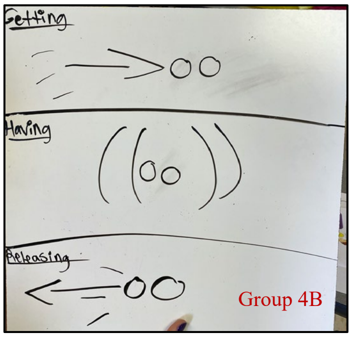
> Mary: We just drew two circles that represent the molecules. For getting energy, they are being pushed together by the two arrows. For having energy, we drew a straight line just to show that it is stable it has the energy in its holding position. Then, releasing energy is showing the molecules like going out different directions <she shakes and moves her hands and fingers in opposite directions>.

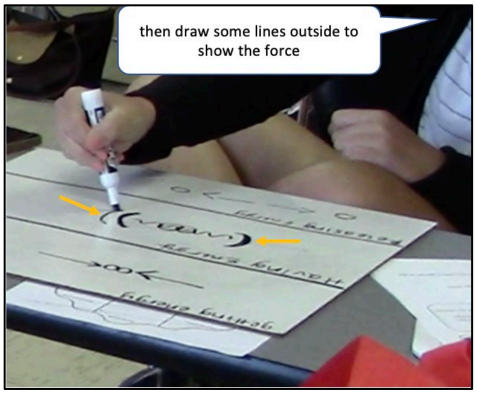


From this excerpt, it was seen that Mary generated an additional gesture to represent releasing energy along with the drawing. Initially, her group used their index fingers to symbolize releasing energy and described the detached atoms and molecular entities going in two different directions. Using all her fingers, Mary emphasized that the atoms and molecular entities of the energy-carrying molecules are removed and move in multiple directions rather than two opposite directions when the molecules release energy. Mary also explicitly indicated that they preferred to use two circles as a generic representation of the energy-carrying molecules: glucose, ATP, and NADH. It seemed that her attempt was influenced by her and her group's experience with practice modeling at the beginning of the instruction, where they learned how to develop a general representation by comparing two or more examples of a phenomenon or object that differed on the surface but shared an underlying structure. In this case, the three energy-carrying molecules differ as to what their molecular configurations look like, but they shared an underlying structure: the way the molecules transfer energy. The configurational aspect of the energy-carrying molecules is packed in two generic circles, while the underlying structure of the transfer of energy (getting, having, and releasing energy) was packed into the model itself.

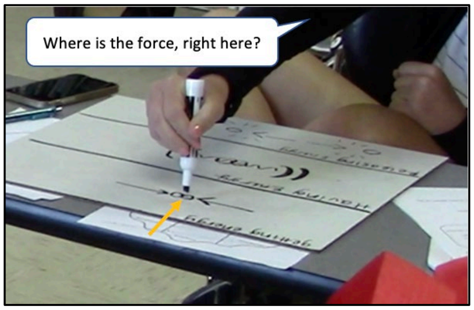
How learners packed ideas and meanings within symbols, gestures, visuals, and verbalizations also influenced one another in their model revisions. During the share-out session, I asked Mary to compare her group's model to another group's model (Group 4B). The reason was that Mary represented the having energy stage by a straight line referring to the molecule being stable, whereas Group 4B represented the getting energy stage by parentheses around the molecule indicating that the molecule was vibrating. Group 1B's initial model is on the left, and Group 4B's initial model is on the right on the next page.





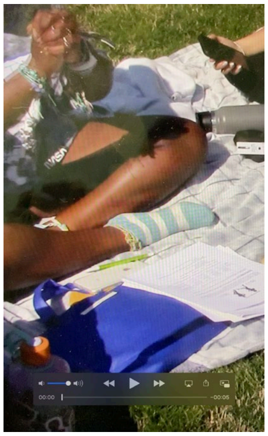


Learners continued to generate semantic expressions during the revision of their initial model. Take this example of the generation of semantic expressions by Group 1B. Based on the class discussion, Mary erased the representation of having energy by saying, “we can draw a squiggly line to represent the vibrations”. She also added parentheses around the molecules and said, “then draw some lines outside to show the force” (As shown on the left). Being influenced by Group 4B’s model, Mary revised her group’s idea of what it means for an energy-carrying molecule to have and hold energy and switch from a straight line indicating that the molecule is stable when having energy to a squiggly line that denotes an unstable, vibrating molecule with high-energy bonds. By adding parentheses around the molecule, she even packed another aspect of the having energy phase into her drawing, which is some force applied to the atoms or molecular entities of the energy-carrying molecule to push them together and once together, hold them together. Building on the force idea for having energy, Mary moved up to the getting energy representation and asked, “Where is the force, right here [pointing at the middle of the molecules]?” (As shown on the left on the next page). Edna responded, “I guess going that way”. Then, Mary drew some lines outside the arrows (As shown on the right on the next page).



This dialogue shows the events of packing meaning into drawings, written and verbal expressions, sound words, and gestures. For instance, the concept of vibrating molecules due to high energy was condensed and described as a squiggly line, two circles were generically referred to as energy-carrying molecules, and the idea that molecules get energy by being pushed against each other was packed into hand gestures showing two index fingers come together, and hands and finger moving in opposite directions indicated molecules releasing energy.

In addition to spontaneously using gestures during model development and revision, learners purposefully and intentionally generated gestures that were packed and imbued with meaning. When Group 3A explained their model during the share-out session, for instance, the introduction of their model was accompanied by Diane's hand gestures. Two videos below captured her gestures specific to getting energy (on the left) and having energy (on the right) phases (Please click on the snapshots below to play the videos and view her gestures).



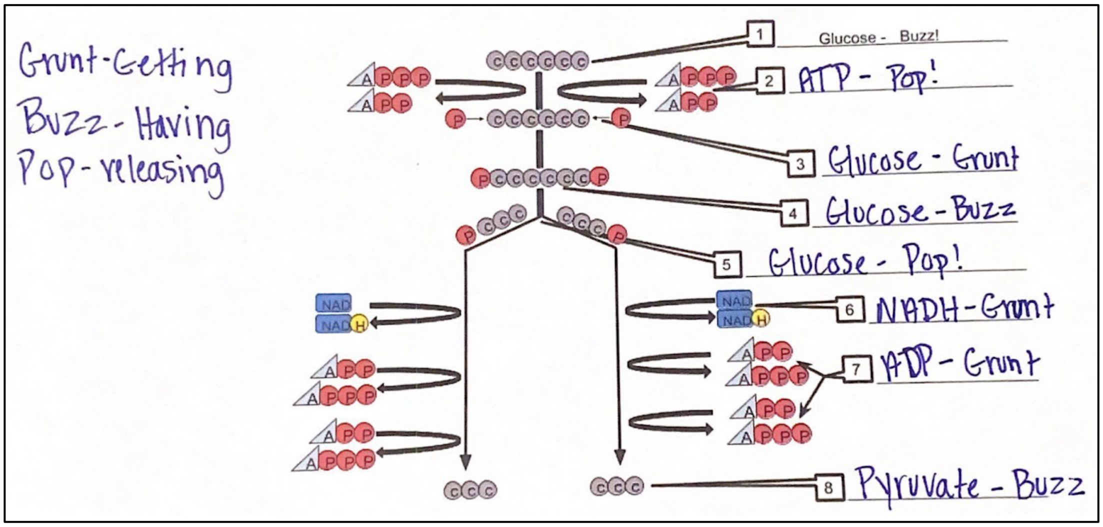
Diane's hand gesture <her fists slowly get closer to each other> for getting energy indicated that for molecules to get energy, some force and pressure need to be applied to the parts of a molecule (e.g., six carbon atoms in glucose or three phosphates in ATP). She showed by her gesture that it was not easy to push the molecules together in getting energy phase. Her gesture for having energy <she clasps her hands tightly together and shakes them> depicted what happens when the atoms or molecular entities of the energy-carrying molecules bond each other, namely becoming highly unstable. Diane packed two main ideas into her gestures: the idea that molecules hold energy when their atoms and molecular entities bond together and the notion of energy-carrying molecules being unstable due to high-energy bonds in them.

Learners also generated some sound words along with their gestures representing the transfer of energy. For instance, Laura's group (Group 4B) used Grunt! for getting energy, Buzz! for having energy, and Pop! for releasing energy (see Figure 23 for the group's final model). Generating and using sound words helped learners build knowledge about the transfer of energy in glycolysis. Learners had a chance to communicate ideas and meanings in their embedded ways of thinking and speaking. This was also evident in learners' reflective essays on their experience learning science with multimodal modeling practices. Edna, for instance, pointed out that embodied actions, in particular generating sound words, used in the modeling process could encourage students to incorporate their existing or everyday ways of thinking and speaking about ideas into science learning. In her reflective essay, Edna wrote: "Making sound effects is such an engaging way to help students remember tricky concepts. It makes connections between school and what children usually enjoy outside of school (TikTok, movies, and YouTube)".

Using embedded ways of thinking and speaking also helped learners engage with science texts in different formats (diagrams, written texts, and graphic novels) and to process scientific information presented in these texts in an accessible way (see Figure 18). Learners' reflective essays also supported this observation about the affordance of multimodal modeling practices that involve learners' self-constructed expressions such as sound words. Sally, for instance, mentioned in her essay that her experience learning with modeling helped her process information. She wrote, "when she introduced the topic, it made me nervous because I am not a 'science person'. However, using modeling with her instruction truly allowed me to process the information better!"

Figure 18

An Illustrative Example of How Learners Engage with the Glycolysis Diagram by Using Self-Constructed Expressions



In this episode, learners further elaborated on the self-constructed modalities that they packed meaning into while learning about and representing the transfer of energy. Learners' gestures, drawings, sound words, and other modalities became a "structuring or deictic resource" that they could talk about and point to during the development, revision, and enrichment of their model (Knain et al., 2021, p. 94). In addition to this, their modalities filled with meaning functioned as deictic resources when learners engaged in reading and interpreting science texts in different formats. Their experience with modeling helped them explore the affordances of modeling in learning scientific ideas by using their linguistic resources that made ideas and concepts accessible to them. Unlike traditional science teaching practices that require learners to move to the disembedded modes of thinking (Blown & Bryce, 2017), which is abstract and symbolic, in learning science, the modeling instruction in this study seemed to be a means of negotiation between scientific language and everyday language.

Episode 3: Unpacking Meaning Through Modalities

The packed meanings generated by learners were unpacked in this episode. Learners used their condensed meanings to make sense of ideas they encountered. Using these packed meanings within a variety of modalities, they unpacked the meanings they constructed when they saw a need for an explanation of what they meant and what they learned. In the following excerpt and Figure 19, Diane uses a variety of modalities that emerged from her experience with the practice of modeling and explains what these modalities mean within the context of the information in a science text she engaged with.

> Diane: In glycolysis, glucose is split into two smaller carbon molecules [the original sentence in the reading]. So, this is saying that glucose is split. So, it's releasing energy <her hands show small explosions by slowly separating her touching fingers and hands> (see Figure 19). Yes, because I remember in the video [the animation she watched in class], it gets split into two molecules <she repeats her gesture presented in Figure 19>, pure bait. I don't know if I said that right, but I remember that from the video. Um, so it's releasing energy for us [referring to her group's model presented in Figure 20] that is a boom because of the big explosion at the end.

Diane first unpacked the meaning of the phrase in the reading, glucose being split, by explaining that it means releasing energy. Then, she deployed her gestures to show what is like for glucose to release energy. Next, she recalled her sound word, boom, which was imbued with meaning (i.e., releasing energy), and she simultaneously gestured an explosion to unpack the meaning of her sound word, boom.

Figure 19

Diane Using Her Hand Gestures to Represent Releasing Energy While Explaining the Information in the Text

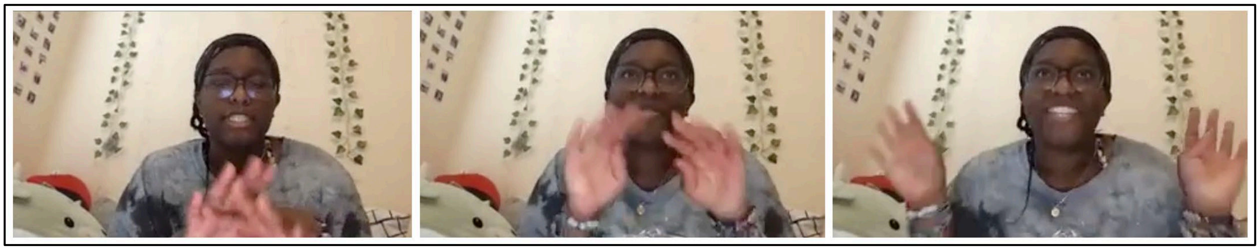
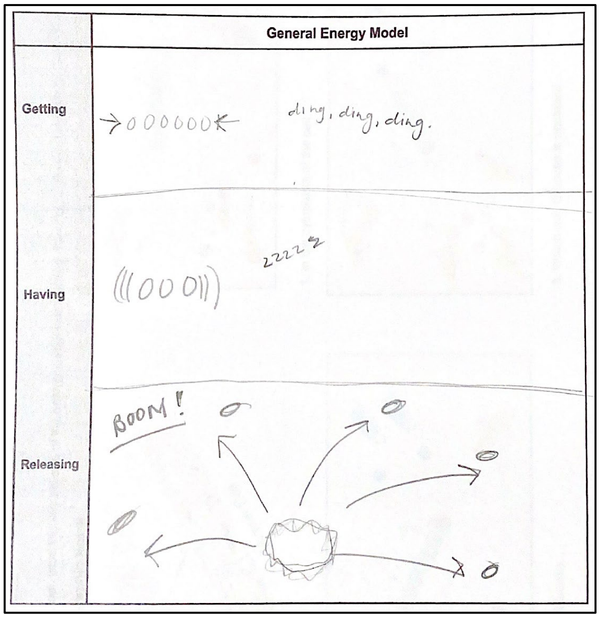


Figure 20

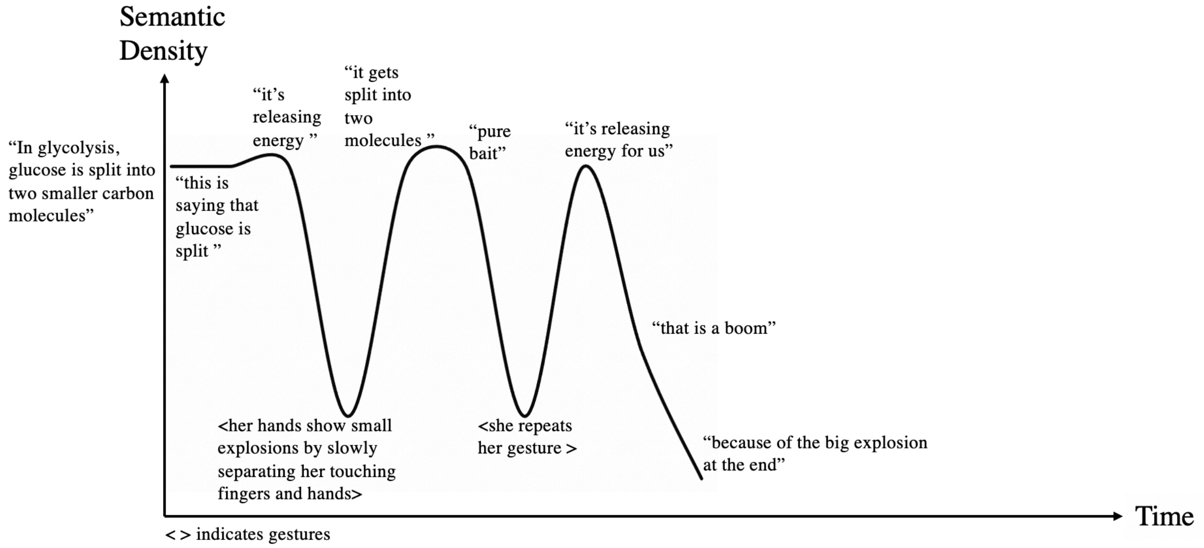
Diane's Final Group Model



As detailed in her semantic profile (see Figure 21), Diane repeatedly moved from condensed meanings packed in symbols, phrases, and expressions towards simpler meanings that emerged through the use of other modalities such as gestures and everyday expressions, decreasing the semantic density. Her profile portrayed a series of unpacking moments as downward shifts (starting with the packed meanings) while she unpacked symbols, phrases, and expressions that were imbued with meanings and emerged in the process of developing a model and using the model itself for knowledge building. For instance, Diane unpacked the meaning of a technical phrase, "glucose splitting into two smaller carbon molecules", in the text when she used her hand gesture to represent an explosion that refers to glucose splitting. In another instance, Diane decreased the semantic density of another technical, complex idea "releasing energy" when she used the sound word "Boom", which was part of her model. This shift was followed by a downward shift in meaning when she further unpacked the meaning of "Boom" by referring to "the big explosion" that she recalled from modeling instruction.

Figure 21

The Semantic Profile of Diane Unpacking Meaning Through Diverse Modalities



Diane employed a set of modalities, most of which came from her model. These modalities with packed meanings included applying a label, such as “boom” or “releasing”; demonstrating an action from the model, such as gesturing an explosion; and, employing an insight gleaned from the animated video about glycolysis, such as attributing the cause of releasing to the explosion in the video. Diane used packed meanings grounded in her personal linguistic resources to process the reading and unpacked what she meant through her modalities.

In another instance of unpacking the ideas and concepts that learners encountered in the science text by referring to their modeling experience, Melissa, read the following sentence from the text during her interview: “As a result, glucose is highly unstable, or active”. She then explained what it means for a glucose molecule to be unstable by saying

> That made me really refer back to my model [see Figure 22 for the model], when we went back and adjusted our models, I went back and added different lines to show that

> like having energy doesn't mean it's just in like a calm state, but it's in a state that means it's like something is gonna happen like it's not, it's not just like all necessarily balanced and at rest.

Similarly, Taylor, Edna, and Melissa explained what it means to be unstable by revisiting their modeling experience including multiple modalities, in particular their hand gestures, sound words, and drawing respectively, to represent getting, having, and releasing energy. Taylor referred to her hand gesture and verbalized, "when it's unstable that means it's probably about to explode. Because we did the hand gestures, where when you're like trying to come together and then it comes together and then explodes". Edna recalled her sound word for having energy and said,

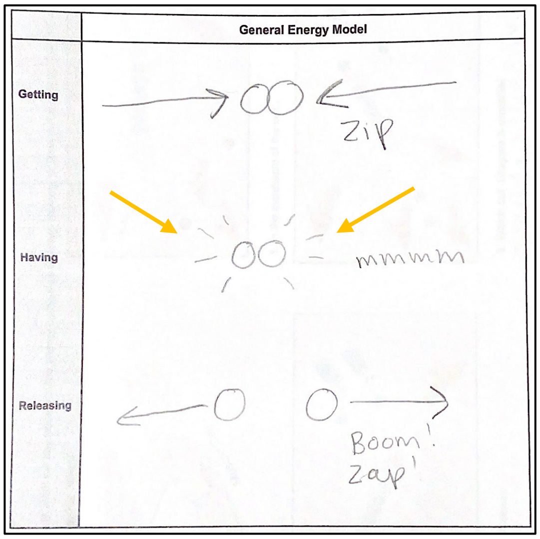
> As a result, the glucose is highly unstable or active and that means definitely having energy. Because we talked about how when this process happens, the molecules then very charged up, which is why we came up with the sound [Uhhh]. To begin with, because it was kind of like a vibrating sound of having a lot of energy. So, this would be the sound, which is having energy.

When she was asked to explain what it means for glucose to be unstable, Melissa remembered her group's drawing (see Figure 22) and stated,

> I was thinking about those little lines that we used on our model and how they were representing that it was kind of like holding it. And so, I was thinking that it's kind of like ready to burst, it's kind of like very ready and it's going to pop at any second.

Figure 22

Melissa's Group Model (Final)



It seemed that the modalities that learners generated and packed meanings into during the modeling instruction provided them with tools that can be used to unpack ideas and concepts presented in the text. Learners used the meanings packed in their modalities (drawings, gestures, and sound words) to talk about the idea of energy-carrying molecules being unstable. They explained, for instance, the meaning of unstable by referring to their self-constructed modalities that are part of their models and modeling process.

Unlike learners using their modeling experience to unpack the ideas and concepts they encountered in the text, some learners preferred to unpack the ideas and concepts in the text by generating instantaneous responses that were not mentioned before or used during the model development and instruction. Anna, for instance, unpacked the idea from the text that glucose is unstable by saying,

> It's because the phosphates are being added to it [glucose]. Yeah, so glucose got extra burden, like thinking about you have burden on your shoulders too heavy phosphates in you kind of got this you know like unbalanced. You are unstable. You don't want it, but

> you got it so much extra energy, right, and it's ready to explode, because it's unstable, right?

Anna also gave an instantaneous response when she unpacked the meaning of glucose being unstable by saying, "as a result, the glucose is highly unstable, or active. I'm going to highlight that. And then, I'm going to say that it's going to make like a very loud racket". These examples showed that even though some learners did not directly recall and use the modalities and expressions that they developed during the instruction to unpack ideas and meanings, the way they communicated ideas during the multimodal modeling instruction (i.e., embedded modes of thinking and speaking) was still reflected in their instantaneous responses when they unpacked the ideas in the text during the interviews. For instance, thinking and speaking in their embedded ways, learners explained the idea of being unstable by using phrases such as "you have a burden on your shoulders" and "it's going to make like a very loud racket". The excerpts above provide evidence that the multimodal modeling experience encouraged learners to unpack scientific ideas and meanings confidently and flexibly in their embedded ways of thinking and speaking.

In addition to unpacking ideas and concepts presented in the text during the interviews, learners explained what some specific modalities used in their group's model meant and unpacked the meanings packed into these modalities during the model development. Consider the following dialogue between Laura from Group 4B and me during the model development:

> Ayça: For getting energy, you have three short lines next to the arrow in your group model (see Figure 23). What do they represent?
>
> Laura: It is basically showing that you have to use force to add it in <she pushes the palm of her right hand to the front and then pulls it back> (see Figure 24). Like they don't click together easily. You have to push them hard <she repeats the same gesture>.

Figure 23

A Final Model for the Transfer of Energy Constructed by Group 4B

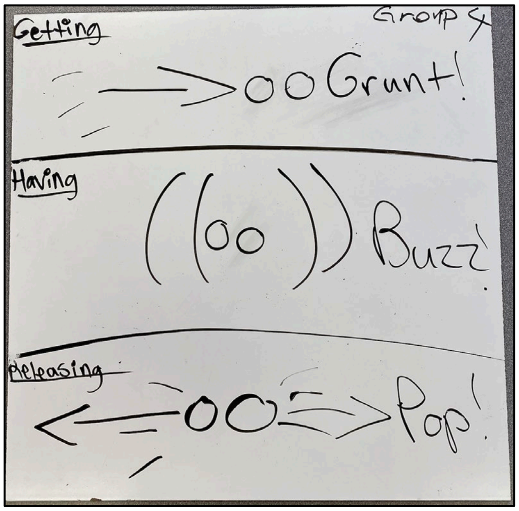


Figure 24

Laura's Hand Gestures Representing the Force Needed for Getting Energy

Early in their model development, Laura and her group packed the idea that for an energy-carrying molecule to get energy requires a force applied to its atoms and molecular entities into three short lines adjacent to the arrow in the getting energy phase. While explaining what these three short lines mean, she simultaneously used hand gestures and verbalization to unpack the meaning condensed into three short lines in the model. Unlike Diane's explosion gesture that she developed during the model development, packed the idea of releasing energy into, and used when needed, Laura spontaneously generated her gesture to support her verbalization to explain a part of her group's model. Admittedly, Laura's gestures created a visual layer of the meaning that was represented through her drawing and eventually unpacked by her verbalization.

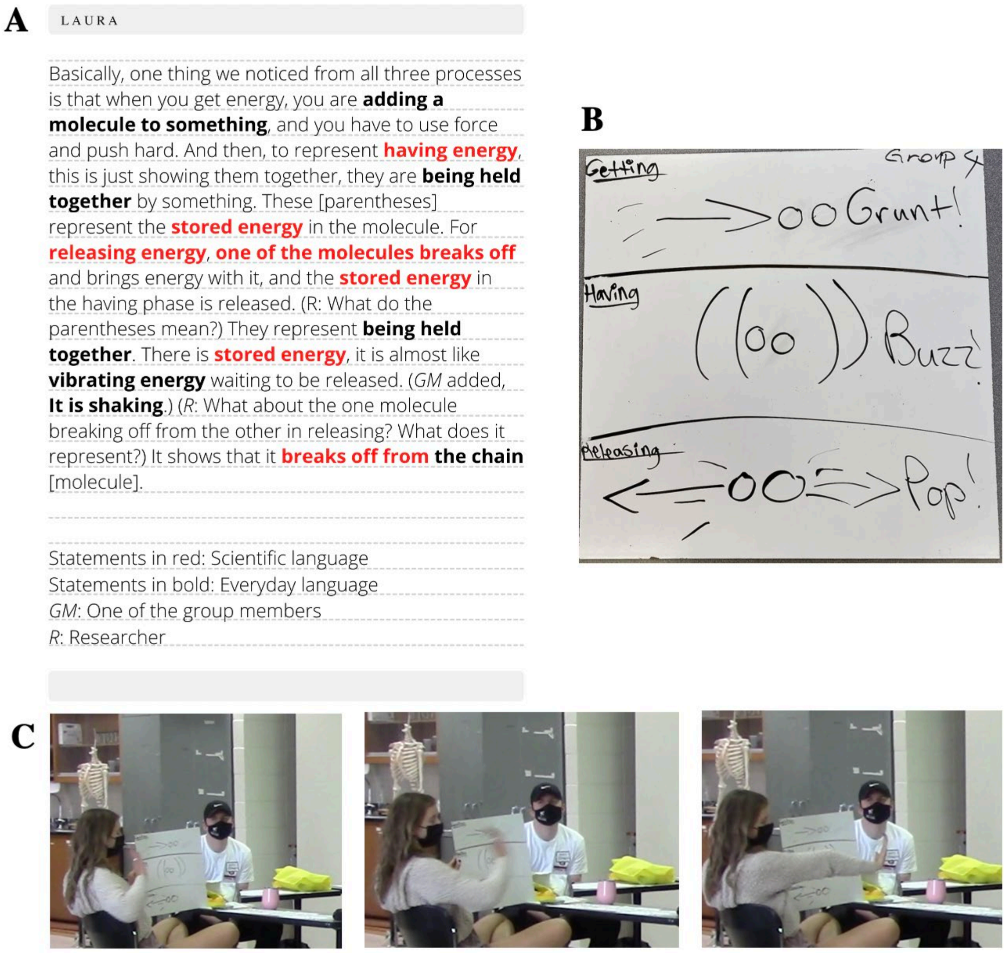
In this episode, students used the packed meanings within their self-constructed modalities to explain ideas and concepts they encountered during both the instruction and interview. This occurred in several ways: unpacking the meanings of specific modalities to interpret ideas and concepts presented in the text, unpacking ideas and concepts presented in the text by referring to specific modalities, unpacking ideas and concepts in the text by generating instantaneous expressions that were not part of (but influenced by) the modeling experience, and unpacking the meanings packed into specific modalities during the model development.

Research Question 2: Switching Between Everyday Language and Scientific Language in Knowledge Building

In what follows, I report the findings of the second research question: In what ways did multimodal modeling practices play a role for learners in their switching between everyday language and scientific language in knowledge building in science? This question did not aim to focus on how scientific language differs from everyday language, but rather on how multimodal modeling practices can help learners use a variety of linguistic resources to engage in knowledge building and switch between scientific language and everyday language, which allows learners to naturally interact with ideas at the heart of disciplinary practices (Bunch & Martin, 2021). The analysis showed that the practice of modeling encouraged learners to switch between everyday words or phrases and scientific words or phrases by facilitating the development of a shared, intermediate language, a bridging discourse (e.g., Gibbons, 2006). This shared, intermediate language developed through/with modeling experience included using both everyday words or phrases and made-up words or phrases to talk about the ideas and concepts related to the transfer of energy in cellular respiration. Learners' use and repetition of these words and phrases indicate a shared way of naming or labeling specific ideas and concepts in knowledge building. For example, Laura from Group 4B shifted from scientific to everyday language and vice versa several times while explaining her group's model to her classmates. Laura explained their model as presented in section A in Figure 25. The semantic profile of her explanation is presented in Figure 26.

Figure 25

Switching Between Everyday Language and Scientific Language Through the Use of Multimodality, A. Laura's Verbal Explanation of The Model, B. Her Group's Model, and C. Her Hand Gestures Coupled with Her Explanation



A

LAURA

Basically, one thing we noticed from all three processes is that when you get energy, you are **adding a molecule to something**, and you have to use force and push hard. And then, to represent **having energy**, this is just showing them together, they are **being held together** by something. These [parentheses] represent the **stored energy** in the molecule. For **releasing energy**, **one of the molecules breaks off** and brings energy with it, and the **stored energy** in the having phase is released. (R: What do the parentheses mean?) They represent **being held together**. There is **stored energy**, it is almost like **vibrating energy** waiting to be released. (*GM* added, **It is shaking**.) (*R*: What about the one molecule breaking off from the other in releasing? What does it represent?) It shows that it **breaks off from the chain** [molecule].

Statements in red: Scientific language

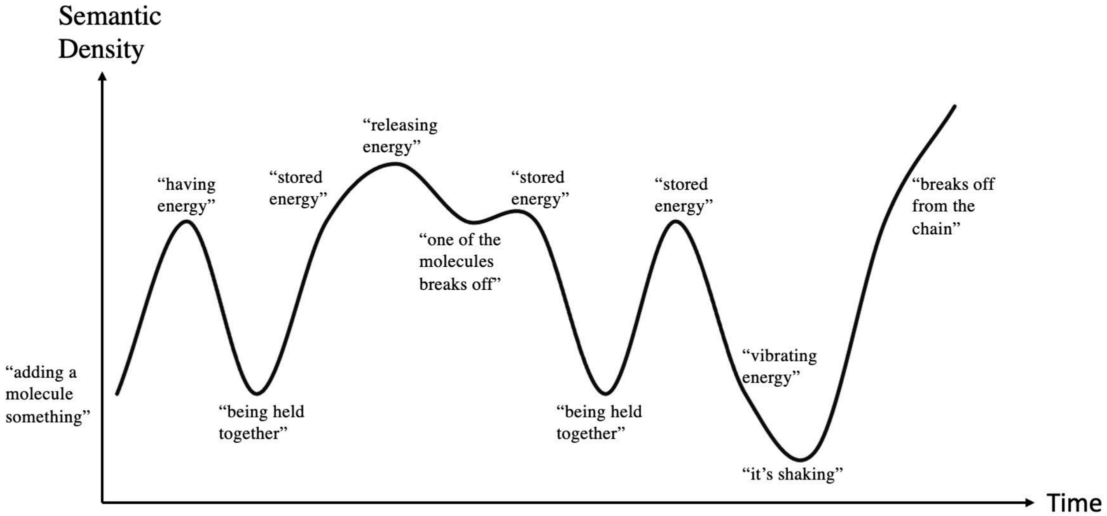
Statements in bold: Everyday language

GM: One of the group members

R: Researcher

Figure 26

The Semantic Profile of Laura Switching Between Everyday Language and Scientific Language



To Laura and her group, getting energy meant adding an atom or a molecular entity to something, which denotes a low semantic density. Here, something represents an energy-carrying molecule, glucose, ATP, or NADH. She avoided using a scientific name or label for energy-carrying molecules. When talking about releasing energy, Laura said, "one of the molecules breaks off", which is a typical science textbook description of molecules releasing energy and is semantically dense. Laura decreased the semantic density when she unpacked another technical term "stored energy" by using the phrases "being held together" and "vibrating energy". Through my questions about her group model, she also referred to their model of molecules having energy, which included the parentheses, circles, and sound word, when she unpacked the meaning of the symbols used in the model (e.g., "being held together" and "vibrating energy"). In addition, one of her group members further decreased the semantic density of the term "stored energy" when he unpacked the term by saying, "it's shaking". Later, Laura switched to an everyday word and referred to the molecular entities of energy-carrying molecules as “the chain”. She preferred to use the word “chain” instead of the molecule and added new complexity to an everyday word, increasing the semantic density of the word. This shift shows that semantic waving occurs in all classroom discourse, and it means that there can also be packed meaning (high semantic density) in everyday discourse and not just in a disciplinary discourse (see Figure 26). Similarly, Laura and her group switched from scientific language to everyday language when she talked about having energy by describing it as “stored energy” (scientific)→ ”vibrating energy” (everyday)→ ”shaking” (everyday), which creates another semantic wave in classroom discourse in response to the shift in semantic density.

In another instance, learners explained what it means for energy-carrying molecules to be unstable by using everyday words and expressions. Group 2B, for instance, shared the following to explain the having energy phase of their model (see Figure 22) where the molecules are unstable: “For having energy, the molecules are kind of feeling tense because there is a lot of like energy vibrating. There is tension and it wants to burst”. In this case, the scientific idea of molecules being unstable due to high-energy bonds in them was represented through “animistic ways of speaking” (Blown & Bryce, 2017). The animistic way of speaking is attributing life, consciousness, and characteristics of living things to inanimate objects. In this study, learners talked about molecules “feeling tense”, “vibrating energy”, and molecules “wanting to burst”. This shows that learners watered the meaning of being unstable down by using these everyday expressions with concrete meanings reflecting animism.

Like the members of Group 2B, Edna from Group 1B used everyday words and phrases to talk about releasing energy in an animistic way during her interview. She verbalized,

> Okay, so, not surprisingly, the glucose soon breaks apart in a chemical reaction. Okay, so that’s releasing energy to me, because it is breaking apart, and that is part of the reason

> we made our sound, Ahhh, because it was almost like the molecules are like screaming because they're being kind of whisked away from each other. So, that is releasing energy to me.

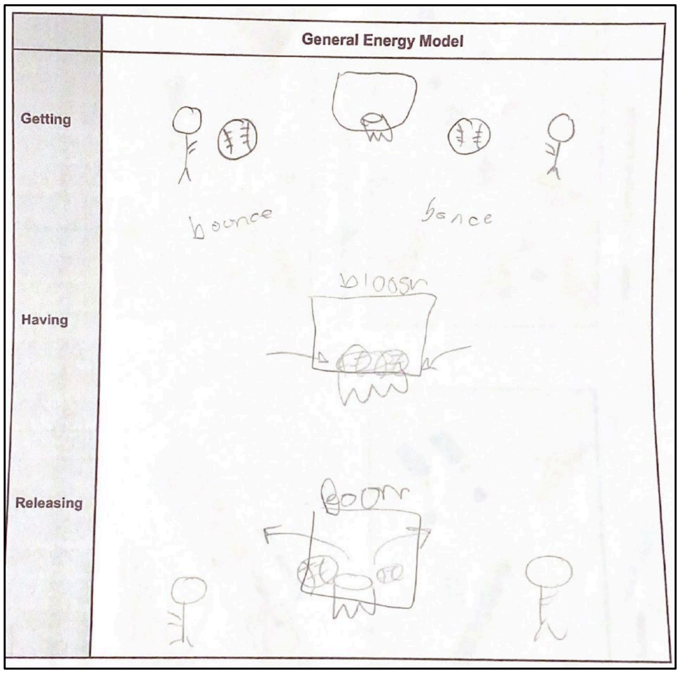
Switching between scientific and everyday language, Edna described the idea of glucose breaking apart while releasing energy as the molecules screaming and being whisked away. Her sound word [Ahhh] appeared to function as a tool that helps her communicate scientific ideas through her everyday way of thinking and speaking.

In addition to incorporating animistic ways of speaking into their discussions, learners also brought their everyday experiences into the context of instruction. For instance, when the members of Group 1B showed how NADH releases energy by removing the lids of their cans at the same time, they observed the springs popping up and flying away. One of them said, "It is just like fireworks". In this case, breaking the energy bonds in molecules, and releasing energy, was associated with shooting fireworks. Multimodal modeling experience offered a great degree of flexibility in the way learners think about ideas by expressing them in everyday language and using their everyday experiences.

In another interesting instance, the recontextualization of the transfer of energy within a basketball analogy helped learners to switch between everyday language and scientific language. Diane from Group 3A explained her group's initial model (see Figure 27) by saying that "these people are trying to shoot a basketball and trying to shoot at the same time [she is referring to getting energy, which is a scientific term]. When they come together [in the hoop], it is like the having stage [having energy], it is like they collide [she is referring to having energy, which is a scientific term]. Once they collide, they bounce back, it is the releasing stage [she is referring to releasing energy, which is a scientific term]". To this group, shooting multiple balls at the same time represented getting energy, getting the balls in the hoop was having energy, and the balls bouncing back from the hoop represented releasing energy. Through this recontextualization, learners integrated some everyday words and phrases, such as shooting, colliding, and bouncing back, into their models and explanations.

Figure 27

The Initial Model Developed by Group 3A

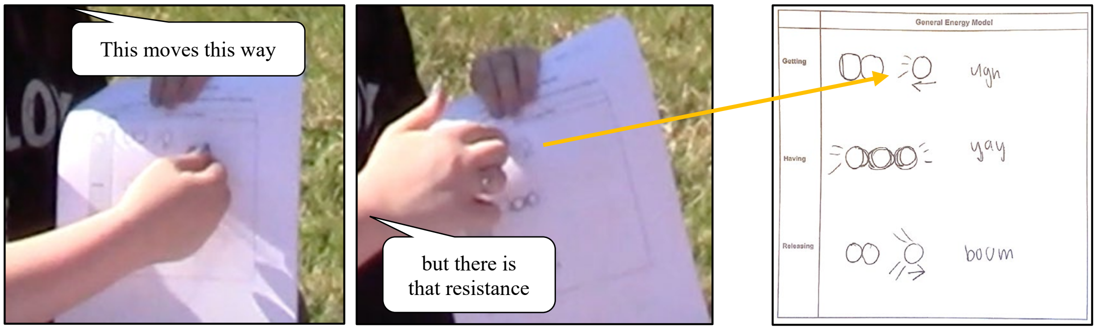


There is also some evidence of recontextualizing scientific terminology within the idea of the transfer of energy. Learners appeared to adopt a scientific concept and applied it to their energy model. For instance, Sally from Group 2A shared the following when I asked her to explain her model.

Ayça: Can you walk me through your model?

Sally: For getting, this is what is already there<points to two circles attached together>. This [the third circle] moves this way<moves her index finger from right to the left

showing how the third circle is attached to other two circles>, but there is that resistance<points to the short lines between the third circle and the other two circles>.



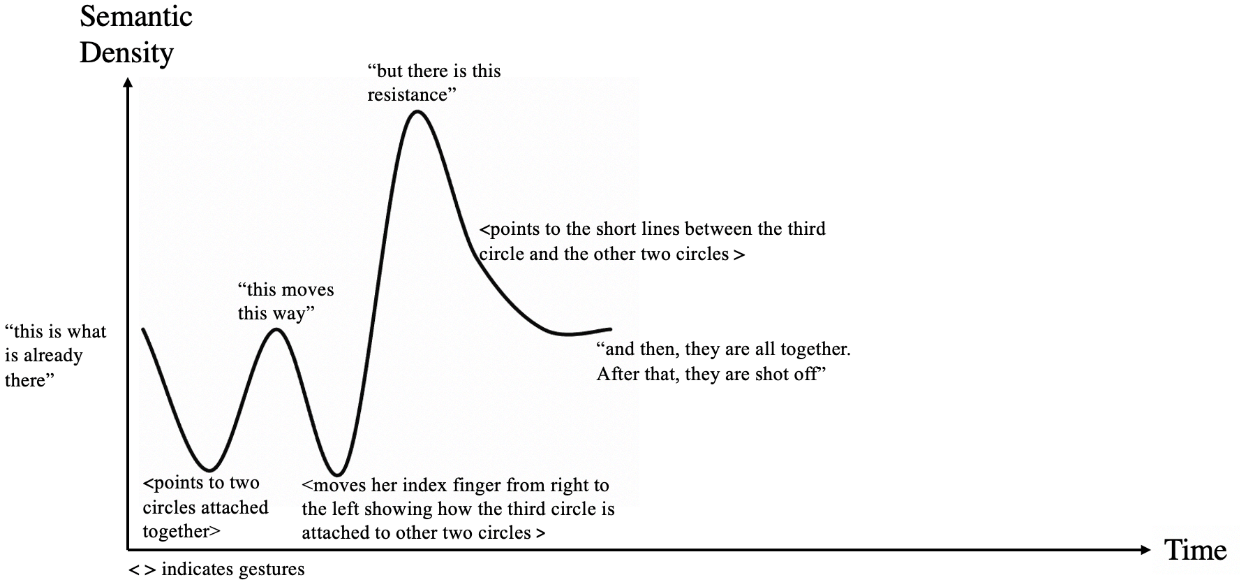
And then, they are all together [having energy]. After that, they are shot off [releasing energy].

Sally used the concept of resistance to explain how hard it is to push the atoms and molecular entities of energy molecules together to get energy. Sally used the concept of resistance to talk about a force that stops the circles (atoms or molecular entities) from moving or makes them move more slowly, such as wind or air resistance. She defined the opposite force applied to the molecules as resistance (see her model above).

Her use of the concept of resistance was influenced by her experience with the physical manipulatives (e.g., ATP or NADH) and energy stories showing that it is hard to attach the third phosphate to ADP (due to like- and unlike-poles) or to squeeze the spring into the can, so it requires some force (see Glucose, ATP, and NAD Energy Story in Appendix B). For instance, when we use a pushing or pulling force to stretch a spring, we use a force over a distance. In this case, the everyday phrases from the energy stories as well as her haptic experience with manipulatives such as the phrase “hard to attach” in the ATP energy story and her haptic experience squeezing the spring into the can were replaced with the concept of resistance. Her use of the concept of resistance was also coupled with her gestures (see her hand gesture above). This recontextualization seemed to make the meaning concrete and easily accessible to her.

Figure 28

The Semantic Profile of Sally Switching Between Everyday Language and Scientific Language

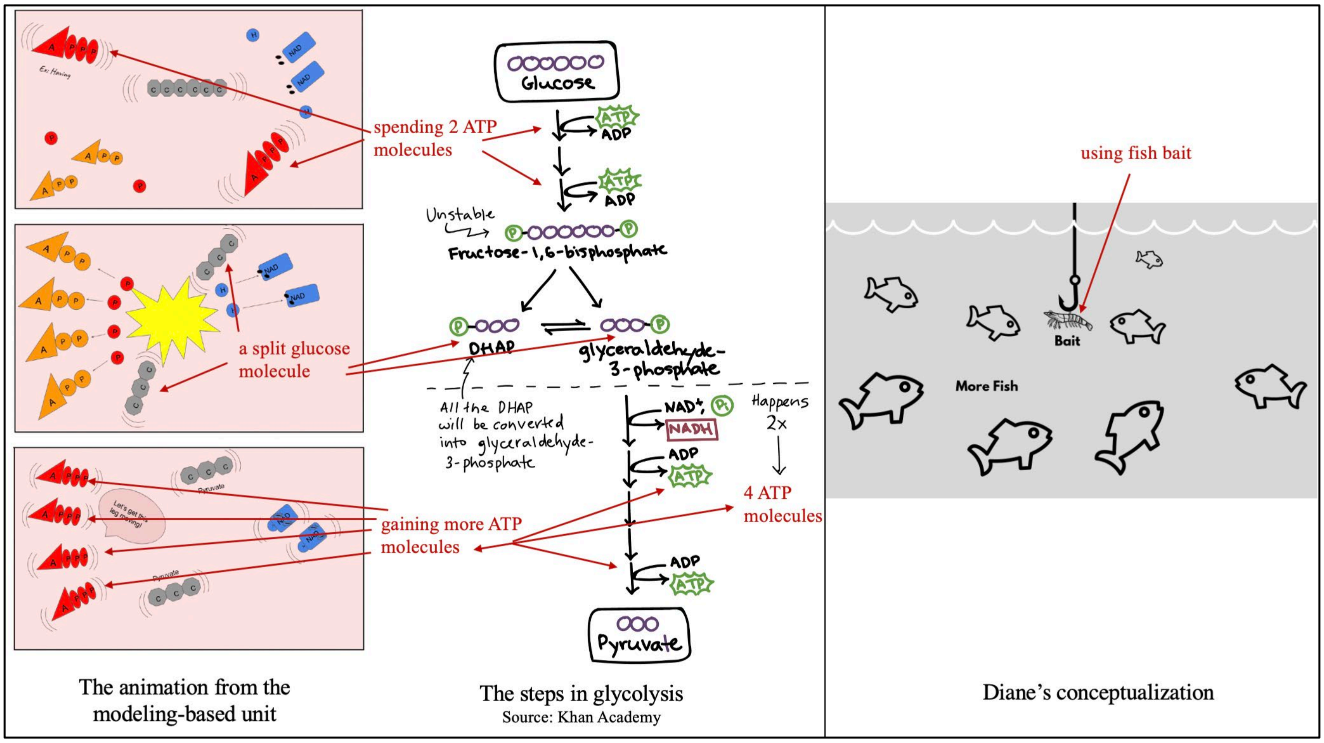


The semantic profile (see Figure 28) of her explanation along with her gestures and drawing (model) also showed that Sally's recontextualization of another scientific term (i.e., resistance) within the idea of the transfer of energy, in particular getting energy, facilitated her switching between everyday language and scientific language. This switch was evident in a series of shifts in the semantic density of the meanings that emerged in the process of modeling. For instance, Sally drew a model of molecules getting, having, and releasing energy, which was packed with meanings and semantically dense. When she used gestures to explain her model, she unpacked the symbols included in her model, decreasing the semantic density. Then she increased the semantic density while connecting two theoretical ideas—i.e., resistance and the transfer of energy (Maton, 2013). Next, she decreased the semantic density by explaining the idea of resistance by using her gesture as part of her familiar way of communicating ideas. Through the multimodal meaning-making that emerged in the practice of modeling, Sally moved between condensed, technical meanings and concrete, simpler meanings, resulting in a series of shifts in the semantic density (increasing vs. decreasing semantic density). An increased semantic density was associated with the use of scientific language along with condensed terms, ideas, or symbols while a decrease in semantic density was observed when students use their everyday way of communicating ideas (Maton, 2020).

Interestingly, I also observed that while switching between everyday language and scientific language through a variety of modalities, learners added new complexity to the everyday words and phrases they used. Building a new complexity around everyday words and phrases happened when learners connected ideas and meanings across modalities they engaged with. Consider the following example. Diane from Group 3A read the following sentence in the science text: In glycolysis, glucose is split into two smaller carbon molecules. Then, she said, "So, this is saying that glucose is split. So, it's releasing energy. Yes, because I remember in the video [the animation she watched in class], it gets split into two molecules, pure bait". The phrase "pure bait" first appeared when she was reading and interpreting the science text about glycolysis during the interview. Diane considers two three-carbon molecules to be pure bait because a split glucose molecule starts the whole process of cellular respiration by spending two ATP molecules at the beginning, yielding a great amount of energy at the end just like fish bait used for catching fish (i.e., using two three-carbon molecules loaded with phosphate from two ATP to produce a lot of energy (4 ATP at the end of glycolysis and 38 ATP at the end of the whole process of aerobic cellular respiration): using fish baits to catch fish). To Diane, the idea that two ATP molecules are invested in the preparatory phase of glycolysis so that the six-carbon glucose molecule can be ready to split evenly into two three-carbon pyruvate molecules, which is called activation energy, is like the idea of fish baits that are used to catch fish. Figure 29 presents how she conceptualizes two three-carbon molecules as "pure bait".

Figure 29

Diane's Conceptualization of a Split Glucose Molecule as Pure Bait



The animation from the modeling-based unit

The steps in glycolysis
Source: Khan Academy

Diane's conceptualization

Note. The steps in glycolysis. (Source: Khan Academy)

She showed that everyday concepts and scientific concepts are in continual interaction and the discourse of science classrooms is a heterogeneous mix of scientific and everyday language (Hsu & Roth, 2014; Vygotsky, 2012). Diane not only picked an everyday phrase to explain what split glucose is and how it functions but also turned it into a little bit more complex phrase (at least within this specific context). She appeared to build some complexity and technicality around an everyday phrase: "pure bait". The modality of "viewing, visual mode" (watching the animated video) helped Diane to switch over from scientific language (i.e., glucose is split into two smaller carbon molecules) to everyday language (i.e., pure bait) (Grapin, 2019).

Overall, the analyses revealed that multimodal modeling practices facilitated switching between everyday words or phrases and scientific words or phrases through the development of a shared, intermediate language. This shared, intermediate language developed through the use of multimodality provided alternative repertoires bonded to ideas and concepts that learners encountered. It also supported learners in reserving and using their familiar ways of thinking and speaking. In this study, learners switched between everyday language and scientific language by incorporating animistic ways of speaking, bringing their everyday experiences into scientific contexts, recontextualizing scientific ideas within everyday contexts, recontextualizing scientific terminology within the concept of the transfer of energy, and adding new levels of complexity to everyday words and phrases. The multimodal aspect of the modeling experience offered a great degree of flexibility in the way learners think about ideas and express them.

Research Question 3: Understanding of Models and Modeling in Knowledge Building

This section reports the findings of the third research question: How did multimodal modeling practices influence learners' understanding of models and modeling in knowledge building in science? In response to the third research question, I identified two types of understanding that regularly surfaced in students' reflective essays and interviews: (a) models as multimodal tools, and (b) models beyond copies of reality.

Models as Multimodal Tools

Before they participated in the modeling instruction and engaged with the modeling case and commentary, learners considered models and modeling to be a single mode of communication (e.g., either a visual or physical representation). Their changing ideas about the multimodal aspect of models and modeling practices were evident in the following illustrative excerpts from the reflective essays written by Edna, Melissa, and Robert. Edna mentioned what she knew about what models look like and who develops a model and how her thinking of models changed after she participated in the practice of modeling. She wrote,

> I enjoyed this lesson because I saw how models can be tied into kinesthetic, audio/visual, and artistic learning. Beforehand, I was under the impression that models consisted of things like T-charts, spreadsheets, or graphic organizers. I thought that they were very cut-and-dry, and always provided or jointly instructed by the teacher. Aycha showed us how models can be constructed by the students, integrated with different modes like kinesthetic movements and verbal sounds.

Not surprisingly, learners had some naïve conceptions about what models are and who gets to develop models in science classrooms. Edna described models as T-charts, spreadsheets, and graphic organizers in her reflective essay. She thought that models are generated and provided by teachers. Based on her prior teaching and learning experience, she did not think that students could develop models in science learning. After participating in the modeling instruction and reading about the modeling case and commentary, she realized that models could involve multiple modalities such as gestures and sound words and that models can be constructed by learners. As suggested by LCT (Maton, 2013; Doran et al., 2021), Edna's experience represents a horizontal knowledge-building experience where learners are encouraged to use their emergent language resources and work together to generate knowledge rather than a vertical one that values the knowledge that is passed from teacher to learner. Highlighting the multimodal aspect of her modeling experience, Melissa also pointed out that using different modes of communication support learners in developing and refining their ideas in science learning. Melissa wrote,

> We did stand up and act out our model using hands and sound effects (Please click on the snapshot to play the video showing how they use embodied actions and sound effects). This threw the whole thing together and reinforced our conceptual ideas by making us

> hear about other groups' models. This strategy should definitely be used for other concepts. Students would greatly benefit from using so many modes of learning, especially when a concept is difficult to learn.

To Melissa, using gestures and sound words along with drawn models and sharing them with peers reinforce their ideas about scientific concepts. She thought that multimodal modeling practices should be used to teach other scientific concepts, especially the ones that are challenging for learners. Similarly, Robert emphasized the importance of learning through multiple modes. He thought that students can learn better when scientific ideas and concepts are presented through multimodality. Robert shared the following in his essay.

> One success with modeling for students that I could see was that students have yet another mode to learn the content. I believe that generally each student performs better and more efficiently retains information when they are involved in learning through multiple modes, rather than learning solely through a specific learning style.

Notably, Robert directly associated different modes of communication used in modeling practices with students' learning styles. It seems that he made connections between learning styles (visual, auditory, and kinesthetic) that have been criticized by many scholars and researchers and the multimodal aspect of modeling instruction. While multimodality includes different modes such as visuals, sounds, and gestures, it is not considered one of the learning styles. As the main takeaway from their experience learning with multimodal modeling practices, learners realized that developing and using models is not an independent mode, but rather needs to be integrated with different modes of representations (embodied actions, depictions, visualizations, and verbalizations).

Interestingly, learners expressed that models as multimodal tools could help students connect their everyday ways of speaking and thinking to their science learning. In her reflection, Edna pointed out that embodied actions (in particular, generating sound words) used in the modeling process could encourage students to use their existing or everyday ways of thinking and speaking about ideas. They also mentioned that the modeling instruction in this study can help students learn scientific ideas and concepts. Consider the following excerpts from Edna's reflective essay. She wrote, "making sound effects is such an engaging way to help students remember tricky concepts. It makes connections between school and what children usually enjoy outside of school (TikTok, movies, and YouTube)". Reflecting on her experience learning science with modeling, Edna stated that the multiple modes integrated into modeling such as sound words are engaging and helpful for students to learn scientific concepts. Echoing Edna's (and Melissa's) views on how helpful modeling instruction can be for science learners, Sally commented that "when she introduced the topic, it made me nervous because I am not a 'science person'. However, using modeling with her instruction truly allowed me to process the information better!"

The analysis of the reflective essays written by learners on their knowledge-building experience with models and modeling showed that learners changed or elaborated on their ideas about models and modeling in science learning. The modeling experience they had helped learners realize the importance of using modeling practices that involve multiple modes of communication while learning complex scientific ideas. They appreciated the affordances of modeling in learning scientific ideas by using their linguistic resources that make scientific concepts accessible to them. The modeling instruction in this study seemed to be an encouragement for learners to incorporate their embedded ways of thinking and speaking into their science learning.

Models Beyond Copies of Reality

Another important point learners reflected on was their thinking about what models are, especially, their shift related to the well-known literal interpretation problem (Cheng & Lin, 2015; Lehrer & Schauble, 2012; Schwarz et al., 2009; Tasquier et al., 2016). The following excerpts illustrate how learners reflected on their initial ideas about what models are and how they expanded their view on the nature of models. What supported this shift in their thinking about models and modeling seemed to be the specific approach to modeling in this study. Learners were directed to work from three instances of a phenomenon (i.e., three molecules transferring energy in glycolysis) that share an underlying structure but differ on the surface and to abstract the structural similarities embedded in those instances. This helped them realize that models cannot be smaller versions or copies of real phenomena. For instance, how Sally thought about models and modeling practices is as follows.

> The topic of modeling is very interesting to me. After reading Michelle's case [the modeling case], I was unsure of how to incorporate modeling into an elementary school science class because I also only thought of models being smaller versions of something. I was unsure of how I could bring other forms of modeling into a classroom with such young children. It was super beneficial to see the modeling techniques that we did while working with Ayca in class though!

Before her experience participating in the practice of modeling and reading about the modeling case, Sally believed that models are a smaller version of actual scientific phenomena or events, and she was not sure about how to use modeling practices in her future classrooms. She might also have thought that models are big versions of small things like plant cells. It seems that she thought of models as scale models in general. She found her experience learning science by developing and using models helpful in terms of giving her a sense of what modeling might look like rather than creating a copy of real scientific phenomena. Laura, Melissa, and Anna also shared similar experiences and prior knowledge about what models and modeling are. Laura, for instance, wrote,

> Prior to the lesson, I don't feel like I had much knowledge of models or modeling. After reading the case studies, I feel like I probably would have done something similar to what the fifth graders did if I were asked to create a model. I definitely just thought of models as smaller versions of the real thing!

Sharing her prior knowledge and experience on models and modeling, Laura confessed that what elementary students did when they were asked to develop a model would be like what she would have done if she were asked to develop a model. She thought of models as a smaller version of scientific events and concepts. Melissa agreed with Laura and wrote, "interestingly, before this week I also thought of the word model as the mini-versions or arts and crafts models mentioned in the case study". Similarly, Anna shared the following: "In my experience, only direct replicas are used when thinking about modeling in science elementary school classrooms".

In addition to realizing that their initial ideas about models and modeling are not complete, learners also emphasized that their experience with modeling in this study helped them to understand how one can go about modeling, at least one way of thinking about modeling in science learning. After sharing what she thought models are, for instance, Luci wrote about what she learned about developing models based on the modeling lesson and case.

> We read and analyzed a case called Arts and Crafts with a Side of Science about how young students often have a naïve understanding of what exactly scientific models are. Most simply assume that models are smaller versions of the real thing when in fact, there are various types of models. To be honest, before this week, my own ideas weren't too dissimilar. I now have a much better understanding of the diversity and variability that exists within the realm of scientific models. When you are creating a model, you don't have to create a smaller version of the real thing, you just have to get the main function or idea across.

Luci's articulation that models represent "the main function or idea" points towards a more sophisticated understanding than models representing the phenomenon itself just like a replica. As defined in the framework for K-12 science education, a model is a general representation that "brings certain features into focus while minimizing or obscuring others" (NRC, 2012, p. 56). Luci understood that modelers should strategically decide what to include and what to exclude in a model considering the purpose of the model. Like Luci, Robert also mentioned in his reflective essay that the modeling lesson was helpful for him and his classmates to understand models are not exact copies of reality. He wrote, "Ayca focused on helping us understand that models are not simply exact life-like replicas of what is being examined or discussed in class". The modeling lesson introduced learners to a relatively new perspective on what models are and how to develop a model of scientific events, processes, or concepts. Since learners were asked to work from three instances of a phenomenon (i.e., three molecules transferring energy in glycolysis) that share an underlying structure but differ on the surface and to abstract the structural similarities embedded in those instances, they realized that models are not smaller versions or copies of real phenomena. As the theoretical framework used in this study argues, the purpose of knowledge building through models and modeling is not always simplifying the ideas and concepts and making them concrete (e.g., making a smaller version or copy of phenomena). The purpose is to enhance learners' conceptual understanding of scientific ideas (e.g., models represent "the main function or idea").

CHAPTER 5

DISCUSSION AND CONCLUSION

In this chapter, I discuss three important claims that emerged from the findings of this study in the context of answering the research questions shown in Table 10. After discussing each claim, I discuss the scholarly contributions of the study. I conclude with the implications for practice and research and future research directions.

Table 10

Research Questions and Claims Emerged from the Findings

Research questions	Claims emerged from the findings
RQ1. How did multimodal modeling practices facilitate packing and unpacking meanings in knowledge building in science?	Embodied interactions between learners, materials, and linguistic resources matter in packing and unpacking meanings
RQ2. In what ways did multimodal modeling practices play a role for learners in their switching between everyday language and scientific language in knowledge building in science?	Multimodal modeling practices generate a shared, intermediate language that facilitates a shift between everyday language and scientific language by • encouraging animistic way of thinking and speaking • bringing everyday experience into the context of science instruction • adding new complexity to everyday words and phrases
RQ3. How did multimodal modeling practices influence learners' understanding of models and modeling in knowledge building in science?	Models and modeling can be multimodal and beyond replicas

Discussion of Findings

Embodied Interactions Between Learners, Materials, and Linguistic Resources Matter in Packing and Unpacking Meanings

The classroom videos and interviews provide evidence that learners constantly packed and unpacked ideas and meaning within the context of the transfer of energy in glycolysis through the embodied interactions between learners and learning materials along with other modalities in the specific context of this study. These interactions served as a tool that initiates and continues to facilitate the process of packing and unpacking ideas and meanings in science learning. Regardless of how these interactions started and continued throughout the instruction and interviews, learners engaged in ways that led them to explore and create meanings to participate in science learning by backgrounding scientific language. In nearly all the experiences examined, learners benefitted from the interactions between themselves, materials, and their linguistic resources.

The findings of this study showed that the process of packing meanings was initiated by learners' haptic experience with the physical manipulatives. Haptic experience in education refers to sensations in response to a particular action while learning about a concept (Zohar & Levy, 2021). Knowledge building with haptic experience in science classrooms is helpful for learners when they have no prior embodied experience of the concept they study or when the studied concept is not easy to understand and accessible through a single modality (e.g., visual) and needs to be presented by multimodality (Zacharia, 2015). In this study, learners had limited embodied experience of the force of repulsion that was represented by the magnet set, ATP manipulative. Their limited experience was evident in their reaction to the repelling magnets. Mary, for instance, wondered why the magnets did not stick together while Taylor was surprised to see that the third magnet flew away as soon as she released her fingers pressing down on the magnets. It seemed that the embodied interactions between learners and materials formed the basis for a repelling force between the phosphate groups in ATP. Similarly, learners benefited from their haptic experience because the concept of transfer of energy cannot be perceived through only a single modality such as visual. In this case, learners could have not completely understood the concept of force required to push molecules together to get energy just by looking at a visual about it. They, for instance, should feel the repelling force when they push the third magnet down to show getting energy, which would not be possible while only engaging with visuals. Learners benefited from embodied interactions with manipulatives by connecting the content they learned and their movements (Skulmowski & Rey, 2018). In this study, embodied interactions between learners and materials are highly related to the task (e.g., acting out the energy stories, representing getting, having, and releasing energy). As an example of embodied interactions, learners experienced the action of repelling (the force with which the entities of energy-carrying molecules repel one another) that functioned as the underlying principle for explaining what is like for molecules to get or release energy. Learners built knowledge about this concept through their haptic experience provided by multimodal modeling practices in this study.

Although Zohar and Levy (2019) suggested that learners used gestures when they could not remember a specific scientific term, I found that learners used gestures and other modalities as part of their embedded ways of thinking and speaking about scientific ideas and concepts. I noticed that most of the time learners generated and used their modalities along with some verbal, written, or drawn explanations. The multimodal aspect of learning with modeling appeared to reinforce learners' ideas about the phenomenon they learned by providing them with opportunities to pack and unpack meanings using diverse language resources. While I recognize the importance of using gestures, for instance, to convey information when there is a gap in the learners' lexicon (Goldin-Meadow & Wagner, 2005), I would argue the use of gestures that are only associated with a gap in knowing and using terminology denotes a deficit perspective on linguistic resources that learners bring to learning environments. Utilizing bodily gestures not only provides space for learners to bring a variety of resources that make science learning accessible, but it also promotes a shift from the dominant conceptual framing of science learning (i.e., acultural, unemotional, disembedded, and disembodied) to science learning and teaching practices that are personalized and grounded in emotions and affection, leading to a more culturally relevant pedagogy in science classrooms (Solomon et al., 2022).

Unlike the studies looking at what type of modalities learners generate and use during instruction and what different modalities provided through modeling are (e.g., Márquez et al., 2006; Pierson et al., 2017; Zohar & Levy, 2019), this study focused on what different modalities do for science learners. Multimodality provided learners with multiple ways of condensing meanings (i.e., packing) and unpacking these meanings when needed, which is central to knowledge building in science (Maton, 2020). Building on their embodied experiences, learners condensed meanings they encountered by (re)producing a variety of modalities throughout both the instruction and interviews. Learners elaborated on their models by representing meanings through their gestures, labels, and sound words. This provided multiple avenues for them to participate in science learning by backgrounding scientific language. For instance, the concept of vibrating molecules due to high energy was condensed and described as a squiggly line (as Mary from Group 1 verbalized while drawing this line: "we can draw a squiggly line to represent the vibrations"), two circles were generically referred to as energy-carrying molecules, the idea that molecules get energy by being pushed against each other was packed into hand gestures showing two index fingers come together, and hands and fingers moving in opposite directions indicated that molecules are releasing energy.

Using multimodality also encouraged learners to communicate ideas in their embedded modes of thinking. Embedded modes of thinking serve as a tool for learners to confidently consolidate and recontextualize their use of scientific expressions and use them while learning complex ideas and concepts in science (Blown & Bryce, 2017, Reigh & Miller, 2020). For example, Edna described glucose being unstable as the molecule being charged up along with her sound word, uhhh. In this case, she used a sound word (both as a type of modality and a part of her model) and expressed the idea of unstable by generating a specific sound word, uhhh, which is imbued with meaning. Learners' embedded ways of thinking and speaking helped them engage with science texts in different formats (diagrams, written texts, and graphic novels) and process scientific information presented in these texts in an accessible way. Learners appreciated the multimodal aspect of modeling in learning scientific ideas by using their linguistic resources that make ideas and concepts accessible to them.

Focusing on what different modalities can do for science learners, this study also showed how learners generated and employed diverse modalities that were imbued with meanings during the practice of modeling. These modalities provided them with tools that can be used to unpack ideas and concepts that came up in class discussions or presented in the text, which is an important aspect of knowledge building (Maton, 2020). Learners, for instance, unpacked the meanings packed in their modalities (e.g., drawings, gestures, sound words, and verbal expressions) when they talked about the idea of energy-carrying molecules being unstable. They explained the meaning of unstable by referring to their self-constructed modalities that are part of their models and modeling process. In some cases, learners were not able to directly recall and use the modalities and expressions that they developed during the instruction to unpack ideas and meanings. However, the way they communicated ideas during the multimodal modeling instruction (i.e., embedded modes of thinking and speaking) was still reflected in their instantaneous responses when they unpacked the ideas in the text during the interviews. The multimodal modeling experience in this study appeared to be an efficient way to encourage learners to unpack scientific ideas and meanings in their embedded ways of thinking and speaking.

Multimodal Modeling Practices Generate a Shared, Intermediate Language

This study showed that multimodal modeling practices have the potential to generate a shared, intermediate language that helps learners switch between everyday (embedded or familiar ways of thinking and speaking) and scientific (disembedded or unfamiliar ways of thinking and speaking) language. This shared, intermediate language developed through/with the multimodal modeling experience included using both everyday words or phrases and made-up words or phrases to talk about ideas and concepts related to the transfer of energy in cellular respiration where they saw fit. The fact that learners used and repeated these words and phrases indicates a shared way of naming or labeling specific ideas and concepts in knowledge building. To develop a conceptual understanding of science, it is imperative that learners switch between everyday language and scientific language while building knowledge (Maton, 2013). Solomon (1983) suggested:

> The deepest levels of understanding are achieved neither in the abstract heights of ‘pure’ physics, nor by a struggle to eliminate the inexact structures of social communication, but

> by the fluency and discrimination with which we learn to move between these two contrasting domains of knowledge. (Solomon, 1983, p. 58)

Switching between scientific and everyday language, for instance, Edna described the idea of glucose breaking apart while releasing energy as the molecule screaming and being whisked away. Her sound word (Ahhh) appeared to function as a tool that helped her translate her scientific way of thinking (molecules releasing energy) and speaking into her everyday way of thinking and speaking (molecules screaming and being whisked away). Similarly, learners in this study watered the meaning of being unstable (as scientific language) down by using these everyday expressions with concrete meanings. To do so, they either brought their everyday lives and direct experiences into the context or recontextualized the transfer of energy within different scientific concepts such as resistance.

The framework of this study suggests that learners should be able to simplify complex scientific ideas and relate them to their everyday lives as well as recontextualize ideas and concepts and relate them to other theoretical ideas (Maton, 2013, 2020). Consider Sally's experience as an example. She used another scientific concept, resistance, to explain how hard it is to push the atoms and molecular entities of energy molecules together to get energy. She defined the opposite force applied to the molecules as resistance. While she recontextualized the transfer of energy within the context of resistance, she used her gestures to unpack and simplify the idea of resistance and how it relates to the transfer of energy. Her recontextualization appeared to make the meaning concrete and easily accessible. This example portrays upward and downward semantic shifts in knowledge building as described by LCT (Maton, 2013). It shows an upward semantic shift when Sally connects the concept of resistance to what happens when the opposite force is applied to the molecules in the phase of getting energy, building upon her existing knowledge. It presents a downward semantic shift when Sally unpacks and simplifies the meaning of resistance using her gestures and explains how resistance relates to the transfer of energy. As shown by Sally's experience, the recontextualization of knowledge, which is an important aspect of building knowledge, requires both upward shifts and downward shifts (Maton, 2013).

Although Sally's recontextualization of the transfer of energy within the context of resistance was not complete, she was able to use her modalities to negotiate between the scientific way of thinking and speaking and her everyday way of thinking and speaking. Learners should be provided with several opportunities to translate disciplinary understandings into everyday language, even if such translations can only ever be partial rather than complete, because of the abstractedness of scientific terms and concepts (Lemke, 2004). The multimodal modeling experience in this study offered learners a great degree of flexibility in the way they think about and communicate scientific ideas and concepts while building knowledge in science.

The shared, intermediate language developed through the multimodal modeling experience also promoted an animistic way of thinking and speaking which is a common practice in all grades of education and has been studied extensively in science education research (e.g., Plummer, 2009; Tao et al., 2013, 2020; Valanides et al., 2000; Vosniadou et al., 2004). Kallery and Psillos (2004) showed that early years (pre-primary education) teachers have concerns about their use of animistic expressions in their science teaching practices. Even though elementary teachers tend to think that animism in the early years of science learning can lead to cognitive and emotional problems in young learners, they use animism both consciously and unconsciously in classrooms. Kallery and Psillos (2004) also reported that early years teachers prefer to use animistic ways of thinking and speaking in science classrooms because of a lack of content and pedagogical content knowledge in science. However, in this study animistic ways of thinking and speaking is an important aspect of the shared, intermediate language developed by learners. Indeed, animistic ways of thinking and speaking appeared to be constructive and productive in relation to building knowledge of the scientific ideas and concepts in glycolysis. Using animistic ways of thinking and speaking in science classrooms are acceptable elements of effective pedagogical content explanations because "teachers' pedagogical content knowledge is neither pure science nor it is intended to be" (Treagust & Harrison, 2000, p. 1165). Researchers (e.g., J. L. Lemke) focusing on the influence of language and culture on learning recognize that both young learners and adults experience animistic ways of thinking and speaking as part of their daily life, and therefore, it can be a part of pedagogical practices. For instance, the scientific term cohesion can be described by teachers and learners as water particles being stuck together (Treagust & Harrison, 2000). Lemke (1990) suggested using animism and personification in science teaching as long as both teachers and learners know what is happening within a specific context (i.e., how animistic ways of thinking are related to the context).

Although the theoretical framework used in this study, the Legitimation Code Theory, suggested that scientific terms and expressions are more complex and denser than everyday terms and expressions, I found that not to be the case in this study. The findings of this study suggest that while switching between everyday language and scientific language through a variety of modalities, learners added new complexity to the everyday words and phrases they used. Building a new complexity around everyday words and phrases happened when learners connected ideas and meanings across modalities they engaged with. The framework defines scientific (technical) words and phrases as words and phrases that are representative of a specialized domain and that have greater semantic density than everyday words and phrases

(Maton & Doran, 2017). Unlike this conceptualization of scientific vs. everyday words and phrases, I argue that everyday words and phrases can also be complex as Barreto et al. (2021) argued. They can actually be complex in another way that reflects learners' everyday lives and personalized experiences and that is grounded in emotions and affection, which cannot be explained by the theoretical concept of semantic density. This study showed that an everyday phrase, "pure bait", became a denser word in Diane's explanation because it is a phrase that can connect the concept of activation energy used to produce more energy (a split glucose molecule loaded with phosphate from two ATP starts the whole process of cellular respiration by spending two ATP molecules at the beginning, yielding a great amount of energy at the end) to the concept of fish baits used to catch more or bigger fish. She incorporated her direct or indirect experience fishing into her learning of the concept of the transfer of energy in glycolysis. In this case, describing the phrase "pure bait" as being less dense and complex than the phrase activation energy would underestimate how everyday ways of thinking and speaking can have an important role in building knowledge in science. Diane's use of the phrase "pure bait" also provides another example of an upward semantic shift because she condensed the idea of glucose molecules being split in half at the beginning of glycolysis into the phrase "pure bait", making connections between everyday experience/ideas and theoretical ideas (Maton, 2013, 2020).

The shared, intermediate language developed through learners' multimodal modeling experience provided alternative knowledge-building repertoires that are connected to ideas and concepts that learners encountered and constructed (Gibbons, 2006). Being "emergent, not fixed, in flux rather than static", this language supported learners in preserving and using their familiar ways of thinking and speaking in science learning (van Lier, 2004, p. 87). The language generation function of the multimodal modeling experience offered a great degree of flexibility and confidence in the way learners think about scientific ideas and concepts and express them.

Models and Modeling Can Be Multimodal and Beyond Replicas

The analysis revealed that learners have some naïve conceptions about what models are, how they function, and who gets to develop models in science classrooms. Before their experience learning science with models and modeling, learners in this study thought of models and modeling as a way of knowing that is facilitated by only one type of modality rather than multiple modalities. Some studies on models and modeling also conceptualize models in a similar way in which a model incorporates a single modality (either an illustration or three-dimensional physical materials or written expressions (e.g., Baumfalk et al., 2018; Dauer & Long, 2015; Miller & Kastens, 2018; Passmore & Svoboda, 2012). It would be more accurate to view models and modeling practices as multimodal systems and processes (e.g., Dickes et al., 2016; Pierson et al., 2017; Wagh & Gouvea, 2018). After they participated in the modeling lesson and engaged with the modeling case and commentary, learners realized that developing and using models needs to be integrated with different modes of communication (e.g., embodied actions, depictions, visualizations, and verbalizations). Engaging in multimodal modeling practices supports science learning because each modality used offers a distinctive affordance for knowledge building in science (Ainsworth & Prain, 2020). Using diagrams, for instance, helps learners understand why abstraction and simplification are important to represent complex science phenomena two-dimensionally (Lehrer & Schauble, 2015), whereas physical materials and representations provide learners with an opportunity to test design principles and have meaningful personal interactions with phenomena (Manz, 2012; Zohar & Levy, 2019).

Another naïve conception that the learners had about models, was that they are copies of reality or smaller versions of real phenomena. This finding resonates with research such as that of Tasquier, Levrini, and Dillon (2016) who showed that students perceive models as a reproduction that involves “copying ‘something original’ or a real-world phenomenon” (Tasquier et al., 2016, p. 547). Science curricula also cause learners to view models as literal depictions of a phenomenon, rather than simplified, abstract, generative, and explanatory (Cheng & Lin, 2015; Lehrer & Schauble, 2012; Schwarz et al., 2009; Schwarz & White 2005). In this study, learners came to understand that models represent the essential features or functions of a phenomenon rather than representing the phenomenon itself just like a replica. Since learners were asked to work from three instances of a phenomenon (i.e., three molecules transferring energy in glycolysis) that share an underlying structure but differ on the surface and to abstract the structural similarities embedded in those instances, they realized that models cannot be smaller versions or copies of real phenomena. The modeling lesson appeared to introduce learners to a relatively new perspective on what models are and how to develop a model of scientific events, processes, or concepts.

Learners also reflected on what they knew about modelers or model developers. Edna, in her reflective essay, for instance, mentioned that she believed that models are generated and provided by teachers. This is also a very common perception about who gets to develop models in science classrooms. Science curricula and teaching practices promote the idea that models are based on information from some sort of authorities such as textbooks, teachers, or scientists and that learners develop models for their teachers and grades (Schwarz et al., 2009; Schwarz et al., 2012). In this study, learners had a chance to engage in modeling practices that gave them agency (an active process of engagement and authority over their learning) in their process of knowledge building and encouraged them to use their linguistic resources to develop and communicate their models. Learners made their observations by interacting with the materials and each other, collaboratively developed their model to depict and explain how the phenomenon (i.e., the transfer of energy in cellular respiration) works in their embedded ways of thinking and used their model as a revisable tool for knowledge building. This is exactly what we need to focus on when we examine modeling practices in classrooms: “Who is developing the models? For what purpose? In what contexts? For whom are the models useful (the instructor, classroom community, professional community, personal/public community)?” (Schwarz et al., 2022, p. 2). Focusing on these aspects of modeling practices will make science teaching and learning practices expansive, meaningful, and equitable (Schwarz et al., 2022).

Highlighting the multimodal aspect of their modeling experience, learners appreciated how both a model itself and the process of developing it can make science learning meaningful by encouraging students to use their existing or everyday ways of thinking and speaking about ideas in science classrooms. Learners reflected on how using their linguistic resources during the model development and use made the scientific concept in this study accessible to them. The multimodal modeling practices in this study helped learners to connect and recontextualize everyday ways and scientific ways of thinking and communicating in service of equitable, accessible, and meaningful science learning. Modeling practices in general promote effective knowledge-building experiences in science learning, and it requires an understanding of “whose knowledge and ways of communication are being marginalized, and privileged, in the process” (Schwarz et al., 2022, p. 3). Unlike many studies on models and modeling in science education that values only “abstracted representational knowledge” (Schwarz et al., 2022, p. 4), this study aimed to empower non-dominant ways of thinking about and communicating scientific ideas while building knowledge with models and modeling practices. This empowerment that is grounded in an equitable, accessible, meaningful, and culturally sustaining teaching and learning approach manifested itself as part of the multimodal modeling practices that the participants of this study engaged in.

Modeling is a powerful practice for science learning and teaching in PK-16 settings (Schwarz et al., 2022). For learners to benefit from modeling practices in science learning, the existence of these naïve conceptions about what models are, what models are for, and who gets to develop models in classrooms should not be glossed over. The multimodal modeling experience in this study appeared to be effective in helping learners reflect on their prior ideas and perceptions about the use of modes and modeling practices in science learning. Learners came to understand that models and modeling practices are inherently multimodal, more than literal depictions of scientific phenomena, and provide learners with opportunities to develop agency in their ways of being, thinking, knowing, and communicating while building knowledge in science classrooms.

Conclusion and Scholarly Contributions

Science education researchers have extensively studied models and the practice of modeling, but there is very little research that focuses on the explicit integration of multimodality in modeling practices and how or why it is effective in knowledge building in science classrooms (Ke et al., 2021; Pierson et al., 2021). This study focused on knowledge building in science learning as the primary enterprise, asking how learners take up multimodal modeling practices in service of knowledge building. Focusing on what multiple modalities do for science learners, this study investigated how multimodal modeling practices facilitate packing and unpacking meanings, in what ways multimodal modeling practices play a role in switching between everyday language and scientific language, and how multimodal modeling practices influence learners' understanding of models in knowledge building in science. The findings of this study suggested that multimodal modeling practices (i) facilitate embodied interactions between learners, learning materials, and linguistic resources that help pack and unpack meanings, (ii) encourage the development of a shared, intermediate language that helps learners move from disembedded ways of thinking and speaking to embedded ways of thinking and speaking in science learning, and (iii) expose learners to a better understanding of what meaningful and equitable modeling practices might look like in classroom settings by showing them what actually models are for, how they function, who can develop a model, and whose knowledge contributes to modeling practices while building knowledge in science.

While we know much about the affordances of using multimodality in science teaching and learning, the theoretical and empirical argument of this study contributes new knowledge to the field of science education by highlighting specifically how multimodal modeling practices could develop learners' capacity to pack and unpack meanings in science, negotiate between everyday language and scientific language, and conceptualize a more meaningful and equitable way of engaging in modeling practices in classrooms. As an important contribution, this study focused on both the meaning afforded in each modality and the multiplying of meaning across multiple modalities in knowledge building in science. This study showed that when students self-construct a variety of modes of communication, they flexibly and confidently participate in knowledge building in science. The process of moving across multiple modalities supports learners in deepening their abstract thinking and dynamic knowledge-building (Harman & Burke, 2020). The embodied aspects of knowledge building through modeling helped students incorporate their embedded ways of thinking into science learning unlike traditional approaches to science teaching that require students to express themselves in unfamiliar ways of communicating (Blown & Bryce, 2017). This was evident, for instance, in how learners employed the modeling labels, sound words, gestures, gaze, materials, and instructional experiences to pack and unpack meanings they encountered. Learners utilized the body (and the other modes) as a tool that promotes knowledge building in science learning. This opens up science instruction for learners to use their resources, incorporate their direct experience and everyday life, and thrive in knowledge-building practices in science (Miller & MacDonald, 2019; Schwarz et al., 2022).

Another contribution of this study stemmed from the type of analysis used in this study. Multimodal Interaction Analysis (MIA) illuminated how complex learners' engagement with knowledge building across a variety of modalities and intra-actional spaces was. MIA also helped place more emphasis on multimodal resources by decentralizing the (scientific) language-centric view in science education research (Wilmes & Siry, 2021). In addition to the modeling practices that learners engaged in, MIA in this study empowered learners by framing their interactions and knowledge-building experiences through different modalities and ways of communication rather than foregrounding only privileged ways of communicating in science such as verbal communication. It highlighted the value of embodied interactions in knowledge building, which are personally meaningful to learners. MIA was effective in focusing on how learners embodied complex scientific ideas as well as their feelings about them while developing and using their models (Wilmes & Siry, 2021). The analysis in this study helped position learners in a way that their embodied, authentic, and affective engagement and participation in the modeling practices were not overlooked or undervalued.

This study also contributed to the existing and future work using the LCT framework, in particular the dimension of semantics. Multimodal modeling practices allow more learners to contribute to knowledge building as knowers. It means that multimodal modeling practices promote horizontal (collaborative) knowledge-building experiences rather than vertical ones as seen in traditional science teaching practices where knowledge is passed from expert/teacher to non-expert/learner (Doran et al., 2021). It is an important aspect of knowledge building because it means that learners or knowers have agency in incorporating their knowledge and familiar ways of knowing into model development. This study also showed that the concept of semantic density describing everyday language as being less condensed than scientific language falls short in explaining knowledge-building experiences through multimodal modeling practices in science. The proposed distinction between everyday words and phrases and scientific words and phrases in terms of their complexity and technicality limits the way researchers and educators interpret and judge the knowledge-building experiences of learners. It also causes researchers and educators to adopt a narrow vision of knowledge-building practices centering on the European/Western scientific canon that privileges certain ways of knowing and communicating in science (Schwarz et al., 2022).

Contributing to the contemporary efforts to democratize and humanize science education, this study is an example of empowering learners by recognizing and valuing their cultural, linguistic, and non-linguistic resources in knowledge building in science and by giving them agency in participating in modeling practices and communicating their ideas in science classrooms. This empowerment facilitates a more meaningful and equitable modeling experience for science learners, in response to an urgent need for expanding the common perception of what models and modeling are for, how to engage learners in modeling practices, and what knowledge building with models and modeling look like (Schwarz et al., 2022).

Implications for Practice and Research

This study holds implications for science education and science teacher education research and practices. One important implication of this study is promoting linguistic equity in K-16 science classrooms through multimodal modeling pedagogies. Unlike traditional science teaching practices portraying scientific practices as being grounded in formal, inauthentic, and unemotional ways of communication, this study showed how multimodal modeling practices help learners leverage their linguistic resources and embedded ways of thinking to build knowledge in science learning. Knowledge building through multimodal modeling practices in science can be an avenue for equitable access to and participation in science learning. Why does this matter? We know that the number of students with different cultural and linguistic backgrounds in the nation’s public schools is on the rise. Many students are learning English as a second language and learning science subjects in this scientific language. For all students who are unfamiliar with academic ways of meaning in learning environments, classroom discourses should provide a linguistic bridge between everyday language and scientific language that is associated with curricula (Gibbons, 2006). One question that educators, future educators, and researchers should ask is what promoting equity in science classrooms filled with students who speak different languages and even different dialects of English looks like. Scientific or academic language is nobody’s first language. By over-emphasizing the use of scientific language, educators and researchers might signal to learners with different linguistic and cultural backgrounds that their way of making sense of and communicating ideas is not good enough to learn science. Such messages can confuse or frustrate highly capable learners. For instance, encouraging learners to sketch out ideas through multimodal modeling practices helps them make deeper connections between concepts and organize key ideas in science. The context of this study serves as an example of how we can create an equitable and accessible learning environment by recognizing students' linguistic resources and the modalities they bring to classrooms to build knowledge in science with models and modeling. By doing so, we promote an asset-oriented approach to science teaching, unlike the deficit perspectives on students' language resources. This approach may encourage students to use their embedded ways of thinking and speaking while learning science. It is important for learners to have experience building knowledge in science without prioritizing only scientific language. It is also important for both preservice and inservice teachers to be aware of the use of models and modeling in encouraging students to incorporate their embedded ways of thinking about and communicating scientific ideas.

Another important implication of this study is to broaden the field's perspective on models and modeling in science education. Although there have been many studies on developing and using models in science education, where a model incorporates a single modality such as a diagram, drawing, three-dimensional physical representation, or written explanation (see Baumfalk et al., 2018; Dauer & Long, 2015; Miller & Kastens, 2018; Passmore & Svoboda, 2012; Schwarz et al., 2009), there have been few that have combined two or more of these modalities (see Pierson et al., 2021). It would be more accurate to view models and modeling practices in research and praxis as tools or ways that involve multimodality. Developing and using models is not an independent and stand-alone mode, but rather needs to be integrated with different modes of communication. These different modes should develop in response to the needs of learners, incorporating new modes into meaning-making or transforming existing modes. In addition, this study broadens the perspectives of learners on what models are, what models are for, and who gets to develop models in classrooms. It shows how to empower non-dominant ways of thinking about and communicating scientific ideas and how to give learners agency in developing and using models by encouraging them to use and build on their linguistic resources and direct experiences while building knowledge with multimodal modeling practices.

This study also provides an example of learners using modeling knowledge and experience to read and comprehend science texts. Specifically, it showed how learners can use their modeling experience and knowledge to make sense of ideas in the science text about glycolysis. The nature of elementary curricula is already interdisciplinary. However, elementary teachers tend to spend more time on reading, writing, social studies, and even mathematics while allocating less time to science. Integrating modeling practices into reading classes or vice versa can encourage teachers to engage in more science teaching with models and modeling. This is important to consider while planning professional learning opportunities for both preservice and inservice teachers to provide them with a perspective on how to integrate modeling practices across elementary education curricula (i.e., science, reading, and writing).

Future Research Directions

Future studies should elaborate on the potential utility of multimodal modeling practices by showing how the engagement of K-12 science learners can be examined in terms of embodied intra-actions with the material–environment–students–(para)linguistic resources. Knowledge building in science cannot be viewed as an isolated phenomenon, and modeling practices are not limited to knowledge and experience provided by teachers. Students should have an agency in deciding what kind of knowledge and whose knowledge, interactions, and ways of knowing guide their model development. This is important to consider if we want to provide our students with equitable, accessible, meaningful, and culturally sustaining modeling experience in science learning. It would also be helpful in future research to document how the integration of different modes of communication into modeling practices expands what counts as models and modeling in science education. This might help us learn about the possible affordances of different modes for promoting conceptual, affective, and linguistic understanding in classrooms (Harman & Burke, 2020). Regarding these points, there are several questions that I want to explore in my future work and recommend science education researchers focus on: How can we use multimodal modeling practices to expand students' language resources to add to what they already know? When does everyday language suffice, and when do students need discipline-specific language while building knowledge with models and modeling? How can we use multimodal modeling practices to scaffold science content up rather than watering it down for science learners?

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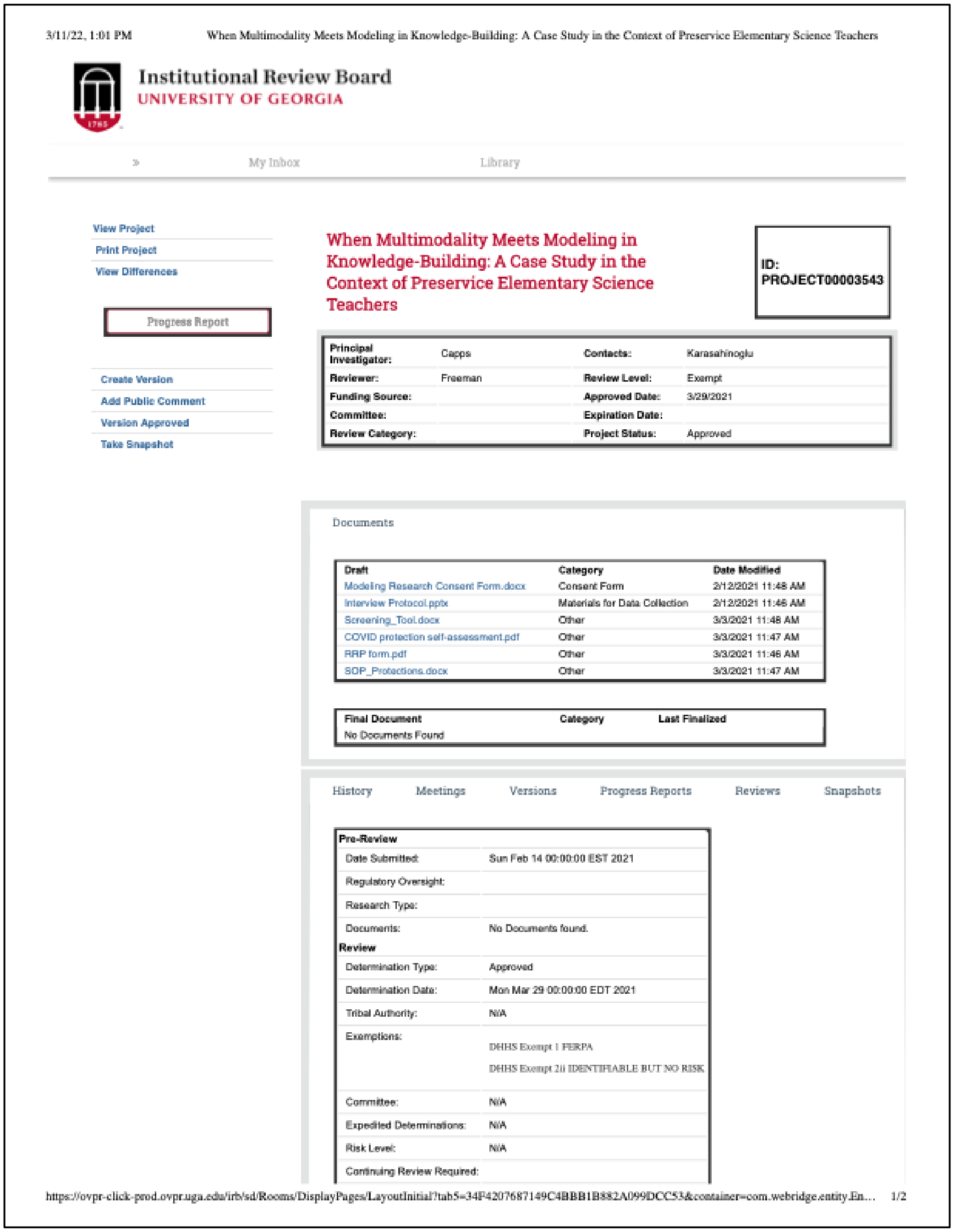
APPENDICES

Appendix

A: IRB Approval Letter



3/11/22, 1:01 PM When Multimodality Meets Modeling in Knowledge-Building: A Case Study in the Context of Preservice Elementary Science Teachers

Institutional Review Board
UNIVERSITY OF GEORGIA

When Multimodality Meets Modeling in Knowledge-Building: A Case Study in the Context of Preservice Elementary Science Teachers

ID: PROJECT00003543

Principal Investigator:	Capps	**Contacts:**	Karasahinoglu
Reviewer:	Freeman	**Review Level:**	Exempt
Funding Source:		**Approved Date:**	3/29/2021
Committee:		**Expiration Date:**	
Review Category:		**Project Status:**	Approved

Documents

Draft	Category	Date Modified
Modeling Research Consent Form.docx	Consent Form	2/12/2021 11:48 AM
Interview Protocol.pptx	Materials for Data Collection	2/12/2021 11:46 AM
Screening_Tool.docx	Other	3/3/2021 11:48 AM
COVID protection self-assessment.pdf	Other	3/3/2021 11:47 AM
RRP form.pdf	Other	3/3/2021 11:46 AM
SOP_Protections.docx	Other	3/3/2021 11:47 AM

Final Document	Category	Last Finalized
No Documents Found		

Pre-Review	
Date Submitted:	Sun Feb 14 00:00:00 EST 2021
Regulatory Oversight:	
Research Type:	
Documents:	No Documents found.
Review	
Determination Type:	Approved
Determination Date:	Mon Mar 29 00:00:00 EDT 2021
Tribal Authority:	N/A
Exemptions:	DHHS Exempt 1 FERPA DHHS Exempt 2ii IDENTIFIABLE BUT NO RISK
Committee:	N/A
Expedited Determinations:	N/A
Risk Level:	N/A
Continuing Review Required:	

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Appendix

B: Modeling Lesson Materials

Meet the Runners

DeShawn is a champion sprinter. His teammate and friend, Janelle, is a distance runner. DeShawn wondered how he would do when running longer distances. One day, he tried running alongside Janelle. At first, he kept up with her. But after three laps, he had to stop because his muscles were tired and hurting. Janelle easily kept going.

<u>Essential question:</u> What happened differently inside Janelle's body that helped her run farther than DeShawn?

To help begin to answer this question, below are some measurements from the last minute before DeShawn stopped running.

	Final Minute of Running				
	Oxygen Used (by Body)	Glucose Used (by Muscles)	ATP Used (by Muscles)	Lactic Acid Produced (by Muscles)	Mitochondria in Leg Muscles
DeShawn	2.0 Liters	5 grams	385 grams	2.6 grams	8% of mass
Janelle	2.7 Liters	3.6 grams	385 grams	0.8 grams	15% of mass

1. Look at the table. Circle the measurements below that are different for the two runners.

   Oxygen Glucose ATP Lactic Acid Mitochondria

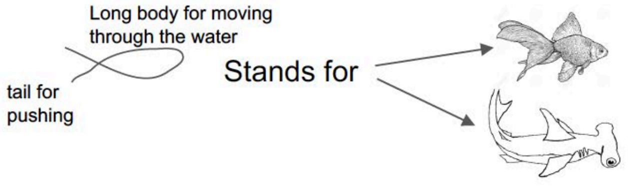
2. Which runner's muscle cells have a greater energy output?
   - ☐ DeShawn's muscles
   - ☐ Janelle's muscles
   - ☐ Their energy output is the same

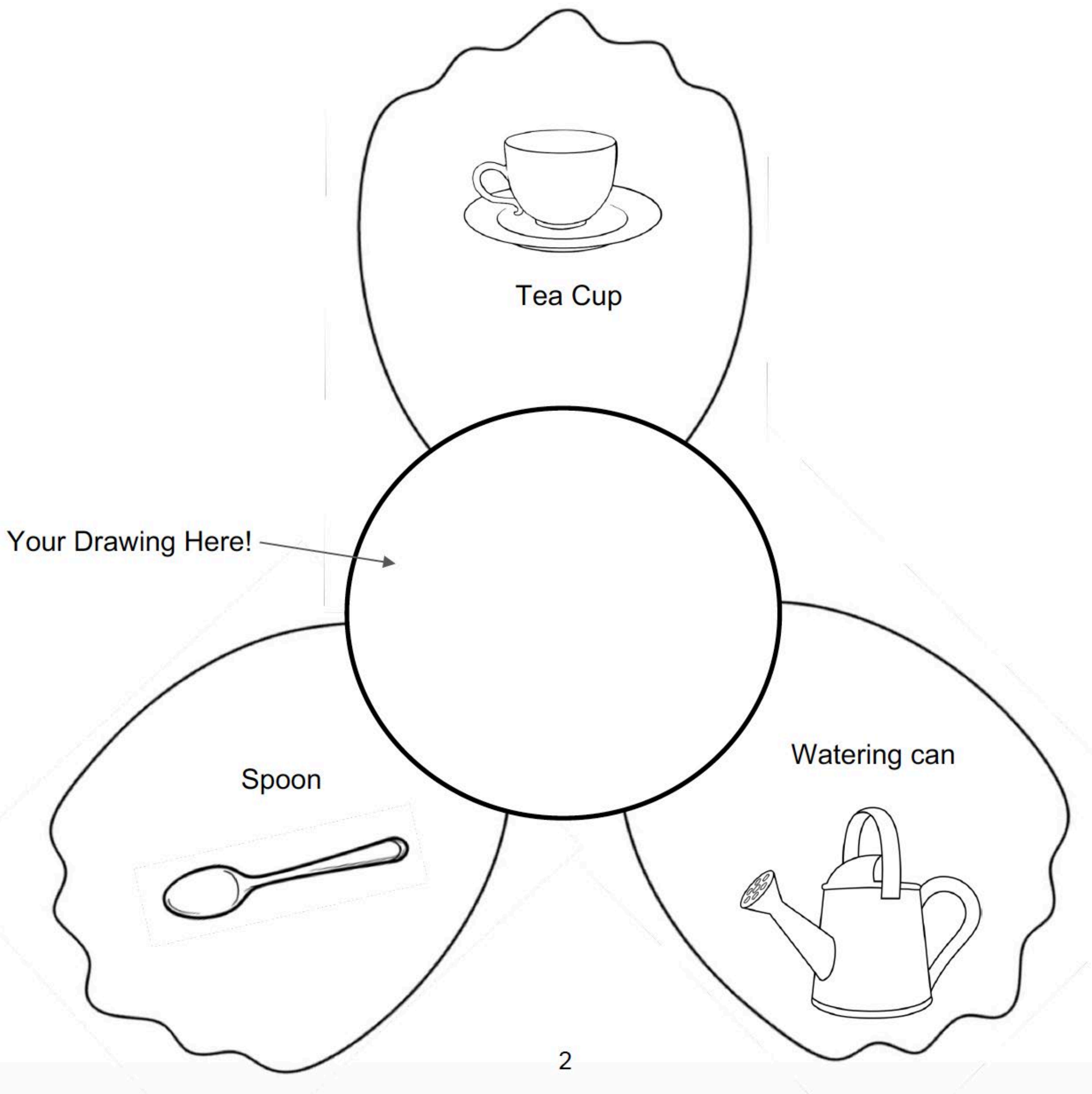
3. Which runner's muscles use food energy better? Be ready to defend your answer.
   - ☐ DeShawn's
   - ☐ Janelle's
   - ☐ They are using food energy equally well

Making a General Model

Draw a picture in the middle of the flower that stands for all three of the petals.

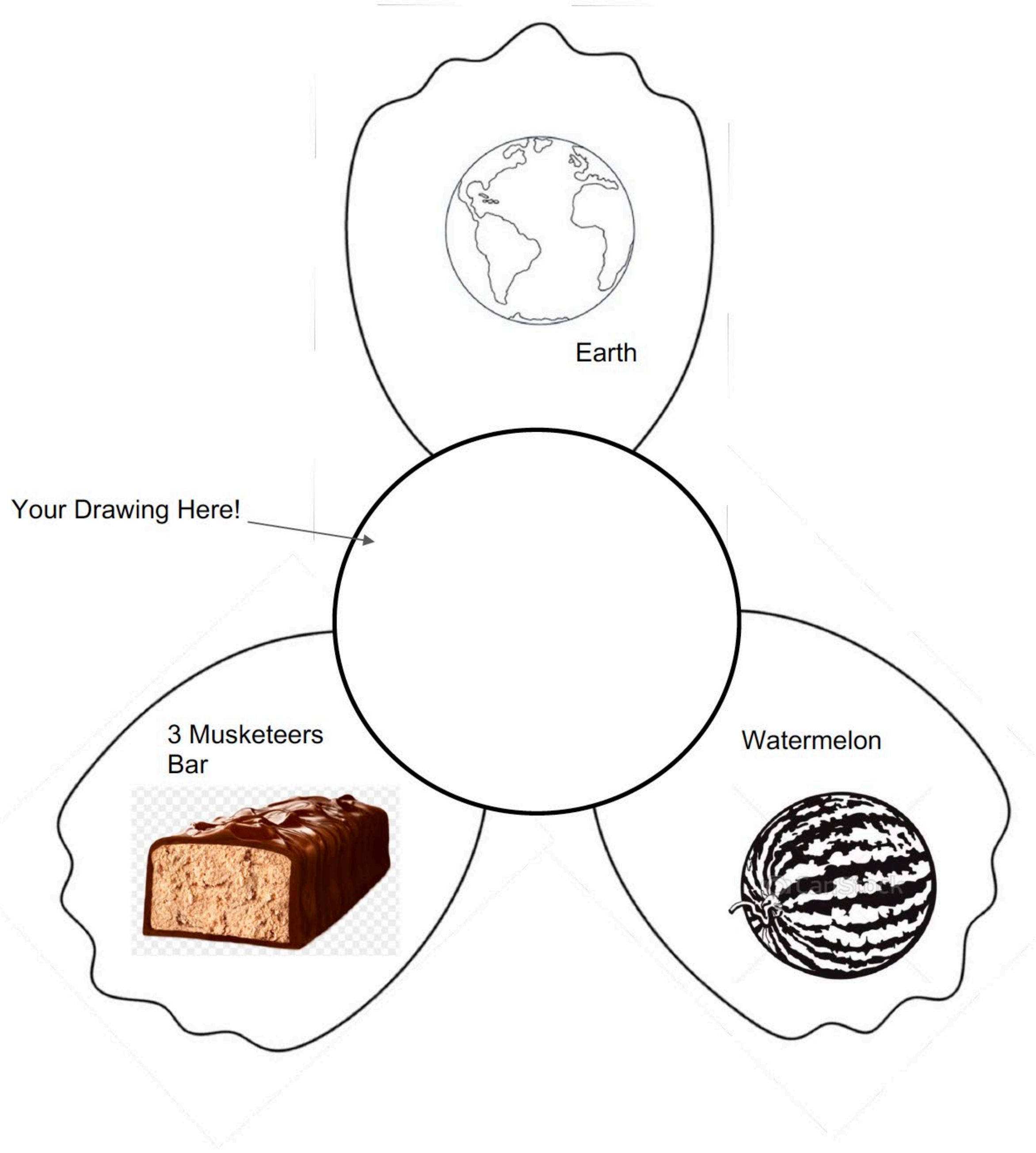
Example:





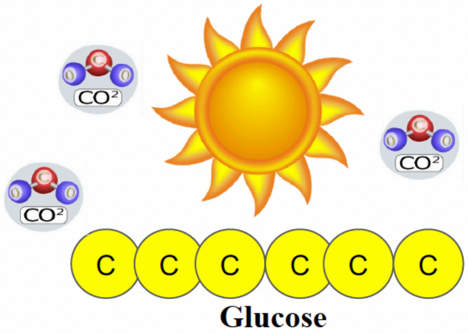
Making a General Model 2

Draw a picture in the middle of the flower that stands for all three of the petals.



Glucose Energy Story

Glucose, a type of sugar, has a lot of energy. It is formed when carbon from the atmosphere bonds together into a six-carbon molecule.



The Actors

- Smaller carbon molecules
- Bonds
- Glucose

The Story

- It takes effort to push carbons together to build a glucose molecule. This happens through photosynthesis.
- When the six carbons are bonded together, glucose has stored energy.
- If you break the bonds of glucose to make smaller carbon molecules, energy is released and available to do work.

Use the Plastic Beads

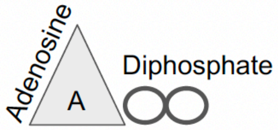
Your Task:

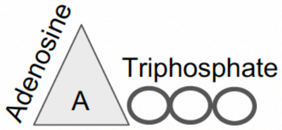
1. Use the plastic beads in the bag to act out the glucose energy story.
    a. First, show the glucose getting energy.
    b. Next, show glucose having energy.
    c. Finally, show how glucose releasing energy.

2. Take the three cards provided and tape them in the correct places on the petal.

ATP Energy Story

ATP (Adenosine Triphosphate) has a lot of energy. It is formed when a third phosphate bonds to **ADP** (Adenosine Diphosphate).





The Actors

- An adenosine base
- Two phosphates
- A third phosphate
- ATP

The Story

- It is hard to attach a third phosphate onto ADP as phosphates repel one another.
- If pushed hard enough, the third phosphate will bond to the ADP, forming ATP.
- The third phosphate can shoot off, releasing ATP's pent-up energy. ATP becomes ADP.

Use the Magnet Set

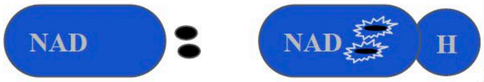
Your task:

1. Use the magnet set in the bag to act out the ATP energy story.
   a. First, show ADP getting energy.
   b. Next, show ATP having energy.
   c. Finally, show ATP releasing energy.

2. Take the three cards provided and tape them in the correct places on the petal.

NADH Energy Story

An **NADH** molecule has a lot of energy.
It is formed when a hydrogen atom bonds to an NAD molecule.



The Actors

- NAD
- H
- Bonds within NAD
- Electrons
- NADH

The Story

- It takes effort to push H onto NAD.
- When H is pushed on, the bonds in NAD squeeze two electrons into higher energy states.
- If the H is removed, the electrons are ejected at high-energy.

Use the Snack Can

Your task:

1. Use the pieces in the bag to act out the NADH energy story.
    a. First, show NAD getting energy.
    b. Next, show NADH having energy.
    c. Finally, show NADH releasing energy.

2. Take the three cards provided and tape them in the correct places on the petal.

Name ______________________________

Period______________

Making a General Energy Model

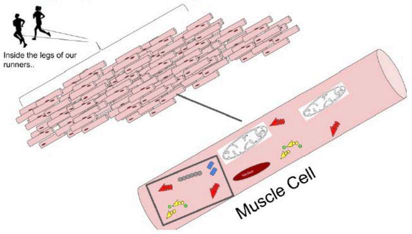
In the box, sketch your group's General Energy Model. Be creative and show the energy as clearly as you can!

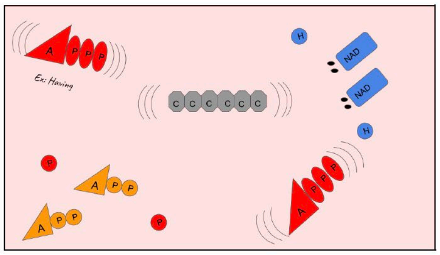
	General Energy Model
Getting	
Having	
Releasing	

Name:_______________
Period:______________

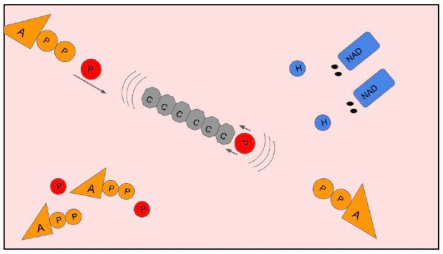
In each numbered panel, label the key actions of the energy carriers as **Getting**, **Having**, or **Releasing** energy. See the example in Panel 1.

Glycolysis: The Graphic Novel

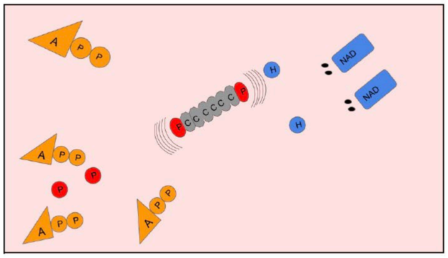




1. In the cytoplasm of the cell...

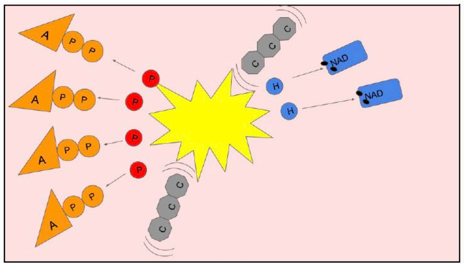


2. ATPs bombard Glucose...

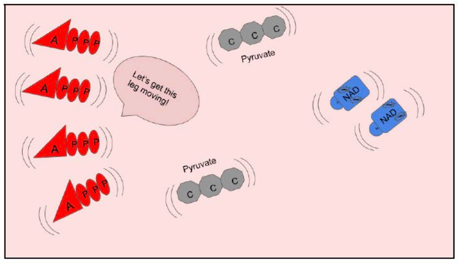


3. Watch out, Glucose is unstable!

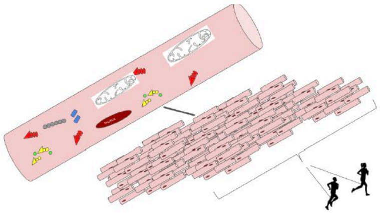
Name:_______________
Period:______________



4. Glucose splits in half like a toothpick.



5. ATPs are back, more than ever! With new friends!

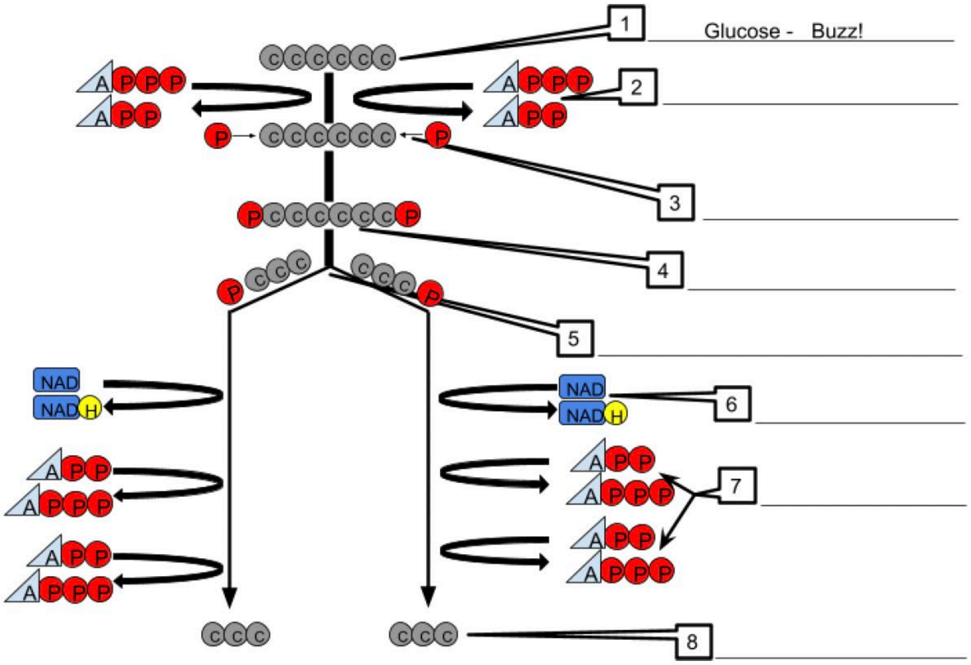


The run continues...

Name: ___________________________

Period: ___________

This diagram shows glycolysis. Write the name of the energy carrier and add the sound that goes with your energy model at each numbered blank. An example is provided.



Appendix

C: Modeling Case and Commentary

Modeling Case:
"Arts and Crafts" with a Side of Science
Michelle J. Petersen

Abstract

This open case discusses an attempt to assess scientific modeling skills within the science curriculum. As a veteran science teacher, I spent much of the school year providing my fifth-grade students with an assortment of model-based lessons aimed at developing their understanding of scientific models. As student groups began to work on their culminating project, a years' worth of planning seemed for naught as most students slipped back into the idea that models are smaller versions of the real thing. Frustrations and questions arose in my mind. How do I fix this? What could I have done differently so that students do not revert to their naïve understanding of models? Could I do that and still give them developmental and creative freedom?

Excitedly, David and Wendy summoned me to their table to describe their model. "We're making the animals. We should make it out of pipe cleaners", Wendy stated as other group members blurted out ideas for using stuffed or plastic animals in their model. Corey finalized their idea with the suggestion of a cardboard box containing all the parts of their ecosystem in miniature form. I subtly reminded them that they need to be able to collect mathematical data that shows how populations can change over time. I wandered away to help other groups, confidently thinking that they would draw on a year-long worth of activities to aid their model development. A few minutes later, I was energetically summoned again as Wendy described how they could make the box with movable parts, like making a jaguar that could eat a sloth. Confidently Isabella stated that it would be "like a pop-up book", and David, always ready to work, asked, "so wait, whose gonna start with the arts and crafts?"

Modeling has moved to the forefront of science education with specific skills identified in the Next Generation Science Standards. Modeling skills range in difficulty from using models to model development. For example, fifth-grade students should be able to "develop a model to describe the movement of matter among plants, animals, and decomposers, and the environment" (NGSS, 2013, para 1). To aid students' modeling abilities this school year, I decided to devote additional time to lessons that would expose them to various types of models and provide opportunities to utilize them. For example, lessons included simulation models that were available online related to plants, natural selection, and circulation. To practice analogical thinking, students compared organelle functions to the functions of items in their daily lives. Students even explored the connection between genes, DNA, and traits by making a graphic organizer, a type of visual model. Based on warm-ups and discussions at the beginning of the year, I knew that students typically viewed models as a different size than the real thing. Thus, I made a concerted effort to avoid using physical models within the classroom. So, throughout the entire year, my overarching goal was to help students achieve understanding that there are various types of models, and they can be created and used for various tasks.

I am currently teaching science at a school in a growing suburban town in the southeastern United States. As a science teacher for sixteen years, I have experienced many shifts in science education. The shift in the standards to more content application skills versus strict knowledge acquisition has been an exciting challenge. As the standards began to incorporate skills alongside the content standards, I worked diligently to create lessons that focused on the application of content versus rote memorization of the information. Modeling was one of the skills that, for me, was the most difficult to incorporate into lessons because I, just like my students, had preconceived notions of what constitutes a scientific model. It was not until I took some graduate-level education classes that I began to learn more about the various types of models. Using that knowledge, I wanted to make sure my lessons incorporated exploring and using various types of models.

During this school year, my lesson planning took on a life of its own because I wanted each major topic to include activities that utilized various models, culminating with one comprehensive modeling assessment. For the assessment, I asked small heterogeneously grouped students to "develop an interactive model that shows how a community of organisms change over time as resources and populations fluctuate". Students were also tasked with determining how to collect data from their model that could provide evidence of their changes in populations. As I began to introduce the activity, murmurs of excited discussion began to erupt throughout various parts of the room. My excitement grew as I heard bits and pieces of their discussions. But my excitement quickly waned as I realized students were defaulting to the apparently ingrained thought that models look like smaller versions of real objects.

As Corey began to draw her idea out on paper, Isabella asked "Are you making like a 3-D cube?" Corey replied, "Yes, it's supposed to look like a box-like the inside of a cardboard box". After their group decided to use a shoebox, the creation of animals was next. Wendy suggested making the jaguar "out of, like, play dough" while Corey wanted to make the animals out of pipe cleaners because you can "form the shape and then paint it black or whatever". As Wendy, Corey, and Isabella continued their discussion about how their model would look, David quietly provided his opinion, saying, "I don't think that's what we have to do". David appeared to be the only one that understood that models do not always appear as smaller versions, but his comment was quickly forgotten when I asked the group about their model. Isabella quickly described their model by saying that they, "are making the animals out of, like, pipe cleaners" and creating their box to be "like a pop-up kids' book".

Since my goal in all of this was to discover what models they were able to create, I stayed out of their decision-making processes as much as possible by simply stating "you are free to choose" and "it's up to you" when they asked what their model should look like. As I listened to their conversations evolve into discussions of appearance instead of functionality, I inwardly groaned and fought off the urge to bury my face in my hands. As I circulated around the room and listened to conversations, I wondered if there was a way to salvage this final assessment from turning into what David had astutely labeled "arts and crafts".

For Reflection and Discussion

1. How could Michelle salvage the final assessment?
2. What could Michelle have done earlier in the year to better ensure that her fifth-grade students understood various types of models?

3. Instead of saying “you are free to choose” and “it’s up to you” what could Michelle have said to her students to help them change their modeling development direction, without removing their autonomy?

Reference
NGSS Lead States. (2013). Next Generation Science Standards. Retrieved from https://www.nextgenscience.org/pe/5-ls2-1-ecosystems-interactions-energy-and-dynamics

Commentary:
The Good, the Bad, and the Misunderstood: Developing and Using Models
Ayça K. Fackler

It is noteworthy that Michelle has made every effort to interest her students in developing and using models. Michelle addressed an important naïve conception about what models are: “models are smaller versions of the real thing”. The idea that models are copies of reality should come as no surprise because of insufficient guidance by the national K-12 science standards and teacher education programs on how to implement model-based lessons. Even though the research literature on learning and teaching with models and modeling is well-established, studies are not enough to shift day-to-day modeling practices and the ways teachers go about using models and modeling in their teaching. This case provides several important insights into how elementary school students think about models. It also offers an opportunity for us, practicing and future teachers of science, to reflect on our model-based instruction and the ways we address students’ naïve perceptions of developing a model in science classrooms. Consider the following points Michelle highlights in her case.

First, it is important to explicitly teach students what models are and what they are for. At the beginning of the school year Michelle took some time to discuss how different types of models can be used for different purposes. According to the case, the students were explicitly asked to “develop an interactive model that shows how a community of organisms change over time as resources and populations fluctuate”. Then, the students were “subtly” reminded that they also needed to collect data from their model. These instructions could have possibly confused students. For instance, were they expected to make a model? Or were they asked to engage in the process of modeling by producing empirical data with their models? If it was both, then, perhaps the instructions should have been more explicit rather than subtle. Additionally, what does an interactive model mean to Michelle’s 5th-grade students? Should we expect students to use a software program to make a model? Or does interactive refer to the idea of the change in a community of organisms over time?

Second, Michelle had her students use their model to collect data, which is a great way to teach how models can be used in scientific processes and to open up the lesson for further elaborations on the topic. As mentioned, Michelle asked her students to collect mathematical data from their model. The instruction for this task might not be easy to understand for 5th graders. Perhaps Michelle could encourage students to define some variables that represent something measurable or predictable and name these variables. Instead, students were asked to make a model that shows how a community of organisms changes over time as resources and populations fluctuate. In this case, what was it about a community of organisms students might want to measure or collect data on? Rather than having a variable called resources, students might be able to change the variable's name to the availability of food, water, shelter, or competition for resources, or even more specifically, the number of predators. Giving students the freedom to solve problems independently is a good strategy, and sometimes less is more. However, in this case, telling the students, "you are free to choose" and "it's up to you" may have led to instructions that were not entirely clear to them. What student models should look like depends on the purpose of their model (explanation, prediction or data collection). There is a fine line between giving the students freedom in deciding how to do a task and giving implicit instruction that students only half-grasp.

Third, David's perception of models, as "arts and crafts", shows that he thinks models represent things (in this case animals) rather than an event, process, or system. Arts and crafts are good materials for creating a poster of things but may not work well in developing a model of phenomena. Even though Michelle extensively discussed different types of models (simulation models or analogical models) with the class and avoided using physical models, the students ended up having "models that looks like smaller versions of the real object". It seems that David and his classmates perceived the task as making a representational model. When students consider developing models as a representational task, they are more likely to create replicas by focusing on explicit features (material aspects) instead of conceptual features (structural aspects) of the phenomenon. This distinction between material aspects and structural aspects (form vs. function) situates models in the context of their use. This is not to say, however, that models represent only structural aspects of a phenomenon. Rather, it suggests that models should explain how a system works (its function), not the form (a specific shape, size, or character) itself. Consider this familiar example, Oreo Cookie Moon Phases. Teachers often have their students make a model that shows the phases of the Moon by using Oreos cookies. Students' models with Oreos may help them learn how to match a moon phase name with a moon phase appearance. However, students will probably not be able to explain what causes the phases of the Moon, how/if lunar phases are related to lunar eclipses, or why there are not eclipses at every full and new moon by using their Oreo model.

Finally, introducing 5th graders to one of the science practices, developing and using models, to her 5th graders, Michelle challenged herself to make sure students have a chance to learn how to think with models in science. She also reflected on her experience teaching about models in this case. Michelle took her students' ideas about models seriously and tried to address them throughout the school year rather than telling her students what she wanted them to know. It is known that elementary science teachers tend to use models as an instructional tool to focus on specific characteristics of an event, object, or process. However, Michelle in this case used models and modeling to facilitate student learning about a complex system, namely changes in a community of organisms over time as resources and populations fluctuate. Even though David's focus on "arts and crafts" has diverted his attention away from the actual modeling task and its purpose, Michelle set up a learning environment that invited students to express their existing ideas and use their inquiry skills.

Appendix

D: Interview Protocol

Background Information

1. What science classes did you take in high school?
2. Did you receive any instruction on cellular respiration before our class? If yes, what do you remember about the instruction on cellular respiration?
3. Did you receive any instruction on scientific models and modeling before our class?
4. What languages do you speak?
5. How do you feel about scientific language?

Practice Thinking Aloud

When you “think aloud” you talk and keep on talking to say your thoughts while you do something. This makes your thoughts visible. The key is to keep talking to say your thoughts. Try these “think aloud” activities.

- Think aloud while imagining a walk from your living room to your nearest street corner.

Practice: Read the text below while thinking aloud. While thinking aloud, underline/highlight each energy carrier, for example ATP or ADP, and write your energy sound word for what it is doing.

A. NADH has a lot of energy. It is a key molecule in cell biology. It’s hard to push the H onto NAD. Once together, NADH is in a high energy state. When the H is removed from NAD, the electrons release.

B. Glucose has a lot of energy. It is an important molecule for cellular respiration. Glucose is formed when energy from the sun pushes carbon atoms together. Glucose can break apart, releasing energy.

Main Task

PART 1: Read the text below aloud. As you read, underline/highlight each energy-carrying molecule, for example NAD or NADH. Near where you underlined the word, write your energy sound word for what it is doing. You can also incorporate some gestures you used during the modeling instruction into your talk.

Example: An NAD gains a hydrogen.

In Glycolysis, glucose is split into two smaller carbon molecules. Glycolysis occurs in two steps. We call the first step “activation.” Activation begins with two ATP molecules sitting in the cytoplasm of the cell. A glucose is floating nearby. Suddenly, the ATP molecules eject a phosphate each! The phosphates push onto the glucose. As a result, the glucose is highly unstable, or “active”.

Not surprisingly, the glucose soon breaks apart in a chemical reaction. The energy released adds phosphates to four ADP molecules, converting them into ATP. It also thrusts hydrogens onto a pair of NAD molecules. Now, four ATP and two NADH molecules are armed and ready to do work in the muscle cell. Overall, glucose loses energy, while ATP and NADH gain energy. This second step of glycolysis is called energy transfer.

PART 2: Read the sentences below aloud. Underline/highlight where you see the energy-carrying molecules and write your energy sound for what they are doing.

A. Glucose contains a fairly large amount of chemical energy.
B. The starting energy for glycolysis is provided by the enzymatic transfer of phosphates from two ATP molecules, converting them to ADP.

PART 3: Another energy carrier is $FADH_2$. It has a base called FAD and two hydrogens pushed on to each end. Once assembled, $FADH_2$ is ready to do work in the cell.

Why do you think $FADH_2$ is ready to do work in the cell?