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Agential Variation Theory: Towards a Post-humanist Performative Account of Undergraduate Biochemistry Students Learning with External Representations of Protein

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy

in

Mathematics and Science Education

by

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DEDICATION

This dissertation is dedicated to the loving memory of my dear grandmother, Xiuying Wei. Her presence in my life was a beacon of love, strength, and wisdom. Though she is no longer with us in the physical realm, her spirit lives on in my heart and has shaped the person I have become today.

EPIGRAPH

The signifier is the sign in redundancy with the sign. All signs are signs of signs. The question is not yet what a given sign signifies but to which other signs it refers, or which signs add themselves to it to form a network without beginning or end that projects its shadow onto an amorphous atmospheric continuum.

Gilles Deleuze and Felix Guattari

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LIST OF ABBREVIATIONS

AR	Augmented Reality
CER	Chemistry Education Research
DBER	Discipline Based Education Research
STEM	Science, Technology, Engineering, and Mathematics

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ABSTRACT OF THE DISSERTATION

Agential Variation Theory: Towards a Post-humanist Performative Account of Undergraduate Biochemistry Students Learning with External Representations of Protein

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Song Wang

Doctor of Philosophy in Mathematics and Science Education

University of California San Diego, 2023
San Diego State University, 2023

Professor Thomas J. Bussey, Chair
Professor Stanley M. Lo, Co-Chair

The central focus of my dissertation concerns the issue of representation. The issue of representation is important for science education research for two reasons: (1) the use of external representation in science teaching and learning, particularly in chemistry education, is ubiquitous as microscopic entities are not directly visible, and (2) the study of student learning relies on linguistic representation of student conceptions as thoughts are not directly visible. Therefore, the issue of representation is an issue of making the invisible visible, more specifically, an issue of making differences, whether differences among submicroscopic entities or differences among students, visible. If we take seriously Gombirch's (1980) notion that scientific images "do not, of course, aim to record what is visible, their purpose is to make visible" (p.185), we must account for the practices of "making visible" and the underlying philosophical assumptions. With a focus on representation, my dissertation sets out to explore the implications of engaging with philosophical assumptions that may unsettle the normative worldview in science education research by working towards three goals: (1) to critically examine the implicit philosophical assumptions, namely representationalism, metaphysical individualism, and humanism, that underpin the current normative worldview in discipline-based science education, (2) to engage with the relational ontology of agential realism and develop agential variation theory as a framework for exploring the potential of conducting chemistry education research from post-humanist perspectives, and (3) to advance qualitative methodology for investigating representational practices in college chemistry education. The findings of my dissertation explore the analytical implications for the theoretical movement and methodological consideration. Starting with an analysis from the cognitive perspective of variation theory, my findings continuously weave in Marton's notion of critical features, Vygotsky's notion of semiotic mediation, and Barad's notion of intra-action to reconfigure the meaning of qualitative interview data. This weaving of multiple theories reconfigured these constructs to semiotic features, signifying practices, and participation of materiality. Coordination multiple theoretical constructs and onto-epistemological standpoints produced a multilayered reading that showed the fluid and situated evolution of external representations' meaning. Chemistry cultural practices such as structural-activity analysis is shown to both constitute and limit the possibility of external representations' meaning. In addition, the materiality of external representations is shown to play an active role in the production of meaning. These findings complement the interpretive perspective of the representational competence model of student learning with representations.

Chapter 1: Introduction

The central focus of this dissertation concerns the issue of representation. In chemistry education, the use of external representation in chemistry teaching and learning is ubiquitous as submicroscopic entities are not directly visible. The importance of representation is illustrated by the central role representations play in chemistry pedagogy and assessment. Raker and Holme (2013) analyzed 18 American Chemical Society (ACS) exams and showed that more than 90% of exam items included external representations (e.g., diagrams, graphs, equations that are used to illustrate, model, and communicate ideas). Visualization has been included as an anchoring concept by the ACS Examination Institute, and the National Academies of Science proposed Developing and Using Models as one of the Science Practices in the Next Generation Science Standards (Holme et al., 2015; The National Research Council, 2012). Given the importance of external representation in chemistry education, significant endeavor in chemistry education research have been dedicated to the investigation of student's understanding of external representations in chemistry (Gabel, 1998; Gilbert and Treagust, 2009; Kozma and Russell, 1997; Kozma and Russell, 2005; Towns et al., 2012).

In addition to the importance of representation as a research topic, the investigation of student's understanding of external representation in chemistry education research also relies on linguistic representation of student's conceptions, for student's thoughts are not directly visible to researchers. The issue of representation is therefore an issue of making the invisible visible, more specifically, an issue of making differences, whether differences among submicroscopic entities or differences between students and experts, visible. Although making differences visible is a central practice in the production of scientific knowledge (Barad, 2007), science instructors and curriculum mostly focus on communicating the content knowledge of scientific disciplines, i.e., the statements of accepted scientific facts articulated under specific research paradigms, with less attention towards the production of scientific knowledge (McComas, Almazroa, & Clough, 1998). Scientific concepts, laws, and theories are often presented as rigid facts, in stark contrast with the way they are debated and communicated within the scientific community. Osborne (1996) argued that the manner in which new knowledge is produced through science is different from the manner in which old knowledge is learned through science pedagogy, and researchers cannot confuse the two as one and the same thing.

In addition to conveying a stereotyped view of science as a series of successful discoveries about facts of nature, a focus on products of science often orients science instruction towards the acceptance of scientific facts. Differences between student conceptions and scientific consensus are often made visible with a deficit-minded practice of othering: conceptions that differ from accepted scientific facts are considered as defective and a hinderance to learning science (Özmen, 2004). Students who hold onto these "misconceptions" are viewed as having deficiency in understanding the world around them, and their misconceptions need to be diagnosed and corrected with pedagogical intervention (Nakhleh, 1992; Barke, Hazari, & Yitbarek, 2008). Representing student conceptions with a deficit mindset shifts the burden of enculturation into the practice of science to students themselves and often lead to a deficit-minded mode of representing student identities. For example, students who do not readily accept scientific facts are often represented as less competent learners than their peers who do (Nakhleh, 1992). In the context of chemistry education research on external representations, the meaning of external representations enacted with content knowledge experts are privileged as legitimate and competent, while students are often framed as in need of developing visual literacy and representational competency to replace their defective ways of thinking with external representations (Schönborn & Anderson, 2009; Popova & Jones, 2021). The way in which differences are made visible through representation has not only epistemological consequences but ethical consequences as well.

On the other hand, as a reaction to practices that frame differences as deficient, a utopic view of non-directive science education consisting of "pure discovery" by the students emerged. Such a view of science education does not account for the historicity of science: the history of science is full of ideas that are incompatible, and discoveries were often arrived at by irrational routes (Kuhn, 1962). When students engage in "pure discovery", it is unclear why they would arrive at the current scientific consensus. Thomas Kuhn (1962) pointed out that scientific research is guided by the philosophical assumptions that form the historically normative worldview and research paradigms. Kuhn coined the term "normal science" to describe scientific research that set out to further articulate the theories and phenomena within the current paradigm. In this sense, research paradigms supply both the targets and the tools for scientific inquiry. For example, the research paradigm of positivism aims to verify a priori hypotheses and relies on controlled experimentation that operationalize variables and measures (Park, Konge, & Artino, 2020). To include the practice of science without trivializing science to a quasi-cultural free process of discovery, we must examine the philosophical assumptions that underpin how differences are made visible in scientific practices.

In order to make the difference among entities in nature visible, answers to ontological questions such as "what is matter?" form the philosophical foundation on which research is built. To illustrate the importance of philosophical foundations in scientific research, particularly the importance of ontology and epistemology for making differences visible, I will use scientists' investigation of electrons and light as an example. In scientific research efforts informed by classical ontology, particles and waves have been thought of as mutually exclusive categories of being. A particle is a bounded entity while a wave lacks such boundaries and propagates across space. The difference between waves and particles is used to exclude certain forms of matter from one of the two ontological categories: classically, being a particle entails not being a wave, and vice versa. Through this practice of marking matter with mutually exclusive ontological labels, different forms of being are accounted for and made intelligible. On the flip side, the stability as well as intelligibility of particle and wave as ontological categories are maintained through treating the difference between particles and waves with a practice of othering.

Particle and wave being mutually exclusive ontological categories entails properties that are unique to each category. For example, waves diffract; particles do not. Shown in Figure 1.1, A double-slit apparatus can make the difference between particle and wave visible experimentally.

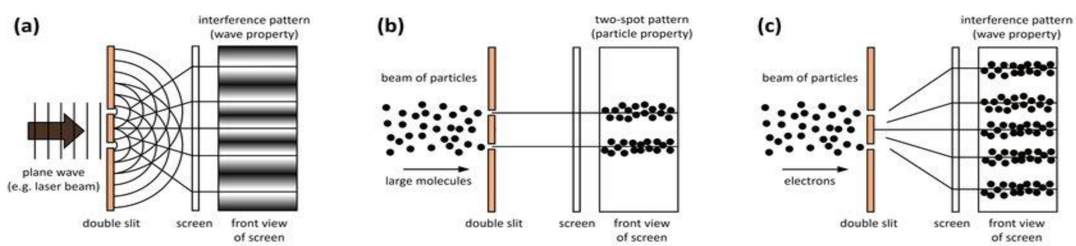

Figure 1.1: Double-slit experiment with (a) laser, (b) large molecules, (c) electrons. Waves passing through the double-slit form an interference pattern on screen (Aydin, 2021).

When a wave passes through a double slit with distance equal or smaller than its wavelength, a diffraction patter appears as the wave travels through both slits simultaneously. On the other hand, particles can only pass through one slit at a time, creating a visibly different pattern on the receiving screen. Utilizing the different patterns produced by particles and waves, a double slit was used as an ontological sorting machine that can be used to categorize things unambiguously into particles and waves. Thomas Young famously used a double slit to generate evidence for the wave theory of light. However, with the emergence of quantum physics, the tools that had helped us categorize nature could not mediate the same kind of categorization when it came to electrons and light without running into immediate problem. The photoelectric effect and double-slit diffraction pattern of electrons challenges the mutual exclusivity of particle and wave as ontological categories. The boundary between particle and wave has become blurry, but that does not mean there is no difference between waves and particles. They are still different without being mutually exclusive ontological categories. This phenomenon central to quantum physics prompt us to rethink the notion of differences. Absolute separation is not necessary for differences to exist (Barad, 2014).

Rethinking Difference

Recalling Thomas Young's double-slit diffraction experiment with light, Barad pointed out that the diffraction pattern of light also calls into question the difference between light and darkness (Barad, 2014). In the light/darkness binary, darkness is the opposite of light. The existence of darkness often entails a lack of light and is conceptualized as lesser and negative. The diffraction phenomenon of light, however, shows that darkness can be a result of adding light to existing light—an abundance rather than a lacking. In chemistry education research, scholars tend to normalize those who readily align with the current values and paradigms of a given scientific community by treating those who do not as lacking, i.e., a deficit mentality. The darkness of ignorance is dispelled by the light of science received through instruction. The way in which differences between light and darkness are made visible has far reaching consequences. As Gloria Anzaldúa wrote in *Borderlands*, the colonizer's story of how darkness is the other of light and sits on the not-light side of darkness/light binary figures darkness as negative, lacking, absence, all of which are then identified with dark skinned people (Anzaldúa, 1987). The diffraction phenomenon challenges the meaning of the difference between darkness and light. An entity already illuminated can become obscured with darkness when new light is added to existing light. Darkness is not the opposite of light, and difference is not the opposite of sameness.

Phenomena in quantum physics suggest that particle and wave are not mutually exclusive categories that describe pre-existing inherent properties of objects. The central issue here is not that particles and waves are no longer different, or that everything is both a particle and a wave. Rather, the crux of the issue is representations' taken-for-granted transparency of referentiality. Particle and waves are thought to refer to things in the universe and transparently represent some property of these things. The difference between particles and waves is thought of as describing differences between things. If we challenge the assumed "thingness" of the world, i.e., if we no longer assume that the primary ontological unit is objects, representations may not refer to objects but rather particular intra-actions through which objects and agencies of observation are constituted (more details in Chapter 2). When objects and agencies of observation cannot be separated in an absolute sense, representations cannot refer to objects only but must be situated in representational practices that constitute both. For example, the representation of light as particles do not refer to light as objects but is situated in the theoretical and experimental configurations that constitute the "particle-ness" of light.

Representation in Chemistry Education Research

Rethinking the notion of difference brought to question the referentiality of representations. Due to the importance of representations in chemistry, the differences between student interpretations of representations and the intended interpretation by instructors have been the interest of educational researchers (Schönborn, Anderson, & Grayson, 2002; Schönborn & Anderson, 2009; Harle & Towns, 2013). If we take seriously Gombirch's (1980) notion that scientific images “do not, of course, aim to record what is visible, their purpose is to make visible” (p.185), we must account for the full set of practices of “making visible”, including the practice of separating subject/object that made vision possible, and see this set of practices as the referent of representations. With the use of technology in chemistry courses becoming a prevalent research theme (Lang & Bodner, 2020), it is important for researchers to reflect on the philosophical foundations that have shaped research as we investigate representations produced by complex technological practices. Echoing Jackson and Mazzei (2011), the current study set out to think methodologically, theoretically, and philosophically together in this time of researching “situations which we no longer know how to react to, in spaces which we no longer know how to describe”. With a focus on representation, this dissertation sets out to explore the implications of engaging with philosophical assumptions that may unsettle the normative worldview in chemistry education research by working towards three goals:

1. Critically examine the often-implicit philosophical assumptions that underpin the current normative worldview in chemistry education.
2. Engage with the relational ontology of agential realism and develop agential variation theory as a framework for exploring the potential of conducting chemical education research from post-humanist perspectives.
3. Advance qualitative methodology for investigating student learning with external representations in college chemistry education.

In order to address these broad goals, several more focused questions are asked in order to address the main research goals. These questions, listed below, are all considered along with their implications.

1. Critically examine the often-implicit philosophical assumptions that underpin the current normative worldview in chemistry education.
    a. What are the philosophical foundations of theoretical frameworks in chemistry education?
    b. What are some implications of committing to these philosophical assumptions?
2. Engage with the relational ontology of agential realism and develop agential variation theory as a framework for exploring the potential of conducting chemical education research from post-humanist perspectives.
    a. What is learning from a relational ontology?
    b. What is the role of external representations in learning from a relational ontology?
3. Advance qualitative methodology for investigating student learning with external representations in college chemistry education.
    a. What is the relationship between data and theory in qualitative research?
    b. How can qualitative research produce meaning differently?

Answering these questions contributes to chemistry education research on external representations by engaging in philosophical, theoretical, and methodological explorations enabled by insights from new materialism (Barad, 2007; Harding, 1988; Haraway, 1997). To illustrate the implications of these explorations, I will think with qualitative data on undergraduate chemistry students working with external representations of G protein and describe the different patterns of meaning that would emerge in the process. This set of interview data is particularly suited as a site for the theoretical and methodological experimentation proposed in this dissertation because of two reasons: (1) theoretically, the different external representations of G protein used during the interviews can provide an example to illustrate the participation of the variation of external representations' materiality in enacting the meaning of G protein, and (2) methodologically, the interview structure where participants were asked to propose a model for G protein function with different external representations can provide a context for experimenting with tracing the differently enacted meaning.

Organization of Dissertation

I will first review current research on representations in chemistry teaching and learning and discuss the often-implicit normative philosophical assumptions that underpinned the theoretical frameworks that guided research. Then, I will use feminist critique of science as a point of departure to explore the possibility of conducting research without a commitment to the normative philosophical assumptions. Next, I will propose a theoretical framework, i.e., agential variation theory, with agential realism as its philosophical foundation. Working both within and against existing methodological boundaries for qualitative research, I will use the same qualitative data set while engaging with a range of theoretical constructs to develop an analysis that explores a mode of qualitative research where both the researcher standpoint and the meaning of data are multiple, fluid, and mutually constitutive. The purpose of engaging with multiple theoretical constructs is not to compare competing analysis of a same social phenomenon, as though learning were a single gestalt object waiting for its one best representation. Rather, the goal is to put different constructs in conversation with each other to produce a thickly-layered analysis of qualitative data and explore knowledge production differently.

The organization of this dissertation can be thought of as three strands of interweaving developments in chemistry education research: a theoretical strand, a methodological strand, and an analytical strand. Although the developments are presented in chapters that are arranged linearly, I want to stress that the theorization process, the methodological considerations, and the analysis of data did not happen chronologically parallel to the order of the chapters. The theorization of learning from a post-humanist, relational ontological standpoint opened up a space for methodological development rather than producing a finished framework to be operationalized and applied in analysis. It is more appropriate to consider the three strands of developments as three aspects of philosophical engagement with relational ontology rather than three sequential stages of research.

In Chapter 2, I will first provide a brief overview of several theoretical frameworks in existing literature and highlight the different types of research that are made possible with these theoretical frameworks. Then I will discuss their shared philosophical assumptions, namely representationalism, humanism, and metaphysical individualism. Following the discussion of these assumptions, I will discuss agential realism as an onto-epistemology that unsettles and moves beyond these assumptions.

In Chapter 3, I will propose agential variation theory as a framework for practicing chemistry education research from an agential realist standpoint. I will first describe the shift from thinking about chemistry knowledge to thinking within cultural practices of chemistry education, then discuss agential variation theory's considerations about learning with external representations.

In Chapter 4, I will describe methodological implications for agential realism in qualitative chemistry education research. I will discuss Haraway's notion of string figure, or SF, and utilize it as a methodological lodestar to explore ways of conduction qualitative research that move beyond producing transparent narratives about student learning underpinned by conceptual categories and themes.

Chapter 5 marks the first of the chapters that describes the SFs from tracing interview events. In this chapter, I will present what emerged from thinking with SF and the transcripts of an interview event with Bobby. I will present analysis of the semiotic features, signifying practices, and the participation of materiality with transcript segments where Bobby was thinking with different external representations. In Chapter 6, 7, and 8, I will present what emerged from thinking with SF and the transcripts of interview events with Jessica, Nicholas, and Mary, respectively. I will present analysis of the semiotic features, signifying practices, and the participation of materiality with transcript segments where the interview participants were thinking with different external representations. The texts presented in these chapters are not meant to serve as an attempt to create a transparent, singular narrative about what "really" happened during each interview event or individual interviewee. Instead, the texts presented in the findings are tracings of thoughts that are made possible to think with when different onto-epistemological considerations, theoretical constructs, data, and materiality intra-act.

In Chapter 9, I will relate the findings to broader considerations of the relationship between education, pedagogy, learning, technology, and chemistry. I will discuss the prospect of conducting cultural studies of chemistry education and highlight the value of creating a transdisciplinary research space by engaging with insights from cultural studies of science and science education.

Chapter 2: Review of Theoretical Frameworks

Research can be framed in different ways using the previous literature, methodologies, or theoretical frameworks of a field of study (Bussey, Lo, & Rasmussen, 2020). The most fundamental framing of research is the philosophical assumptions relating to the general features of the world. The current philosophy of chemistry education can be best described by positivism and realism, i.e., presenting chemistry, and by extension, science, as a linear succession of successful discoveries and placing the emphasis on factual recall with confirmatory experiments (Chamizo, 2013). These philosophical assumptions in research are often carried into practice. Van Berkel et al. (2000) analyzed chemistry textbooks and syllabi representative of the secondary science education in most Western countries and recognized that positivism was prevalent in the dominant school curriculum, accompanied by a pedagogy that centered on initiatory and preparatory training. A positivist educational philosophy and initiatory and preparatory pedagogy are common in post-secondary chemical education as well (Erduran, 2001; Sjöström, 2007, 2013).

To contextualize the development of agential variation theory as moving towards a post-humanist performative framework for investigating chemistry learning and teaching, the following chapter is divided into three sections. First, I will provide an overview of some theoretical frameworks commonly used in chemistry education research. The purpose of this overview is to illustrate the differences among the theoretical perspectives and how the differences enrich chemistry education research. Since this dissertation focuses on external representations in chemistry teaching and learning, I will discuss each theoretical framework with examples from chemistry education research on student learning with external representations. Then, I will discuss three main implicit philosophical assumptions that are shared among the various theoretical frameworks, namely representationalism, metaphysical individualism, and humanism. The arguments and perspectives presented here serves both as a survey of the current theoretical landscape of chemistry education research as well as an outline of the intellectual traditions that have influenced my thinking during the formulation of agential variation theory.

Overview of Theoretical Frameworks

In a literature review focusing on STEM education research in higher education, Bussey et al. (2020) reviewed articles published in major science education and discipline-based education research (DBER) journals from 2000 to 2018. The authors noted that relatively little integrated science or STEM education research was published, and the vast majority of STEM education research in higher education context were conducted in the form of DBER. The authors then characterized the use of theoretical frameworks in mathematics education research, engineering education research, physics education research, chemical education research, and biology education research. In mathematics education research, dominant theoretical perspectives shifted from cognitive theories such as Piagetian constructivism to various social theories including communities of practice, sociocultural perspective, and emergent perspective. In engineering education research, a relatively newer field of DBER compared to others, the use of qualitative research methods has been on the rise and methodology has served as the main framing of research. Social and cognitive theories have been used evenly in research. Similarly, in physics education research, methodology was the primary vertex for framing research. However, the use of theoretical frameworks in physics education leans strongly towards cognitive theories, contrasting that in mathematics and engineering education research. Developed alongside physics education research, chemistry education research shares the use of methodology as the primary vertex for framing, and the use of cognitive theories has been prevalent as well. Lastly, in biology education research, the use of cognitive theories such as Piagetian constructivism and conceptual change is still dominant, and researchers are primarily relying on the data sources and research methodologies that are most prevalent in positivist research.

Framing research differently leads to different research practices and knowledge claims, so examining the differences between the ways in which chemistry education research was framed can shed light on how research is practiced and how learning is represented. In this section, I will give an overview of some theoretical frameworks widely used in the chemistry education research literature, with a focus on the variation between the different perspectives. My review of existing theoretical frameworks is to serve two purposes: 1) to illustrate the productive power of the differences among theoretical frameworks in providing an increasingly rich and complex account of learning, and 2) to provide context for the next section, where I will shift from articulating the differences among the theoretical frameworks to examining the common assumptions of representationalism, metaphysical individualism, and humanism in these theoretical frameworks and the limitations of these assumptions. After discussing the shared philosophical assumptions that underpinned the theoretical frameworks used in chemistry education, I will discuss agential realism, an onto-epistemological framework proposed by Karen Barad, to explore the implications of moving towards a relational ontology beyond the dichotomy of objectivism and constructivism. It is the consideration of these theoretical frameworks, along with agential realism, that propelled the theoretical exploration that I labelled agential variation theory. I will discuss the development of agential variation theory in more detail in Chapter 3.

Cognitive Perspectives on Learning

Cognitive scientists have proposed that the mind functions by recognizing and encoding symbols, then applying rules to manipulate these mental symbols to generate a solution for a problem at hand. Like a computer, the mind has its own structure and programs to process the information being presented, and all humans share the same basic cognitive architecture (Bruer, 2001). The human cognitive architecture can be roughly divided into long-term memory and working memory (Bruer, 2001). As information enters our mind through our sensory systems, some of it is held and processed in our limited working memory, where mental operations are conducted and then recorded for a short time. Although working memory can only process a limited number of information chunks at one time, the amount of information in each chunk can vary greatly (National Research Concil, 2000). Some of the symbols processed in the working memory would then be encoded into long-term memory, which has an associative structure where all the information chunks are interrelated with each other by links rather than individually stored, for later retrieval.

In addition to the declarative long-term memory where events and facts are stored, the long-term memory also has a nondeclarative memory component, where our knowledge of skills and procedures, or production rules, is stored. A production system would look for matches between the symbols in working memory and conditions on procedures in nondeclarative long-term memory. Once a match is made, the corresponding production rules are executed, and the symbols in working memory are modified (Reed, 1999). After several cycles of modification to the symbols in the working memory, a solution will be reached for output. When stimulated with a problem in the external world, the working memory coordinates the declarative and nondeclarative memory to generate a solution. Learning, in this view, is the accumulation of symbol processing algorithms.

The information processing perspective has been utilized to investigate the differences between how experts and novices use and interpret external representations. For example, Kozma and Russell (1997) synthesized findings from studies investigating differences between experts and novices of chemistry and proposed a set of skills that describe how chemists process information with external representations. The difference between experts and novices primarily lines in the way they organize and use their knowledge. Experts have more connections between their knowledge elements, with coherent chunks of information organized around underlying principles. Novices, on the other hand, have fragments of information that correspond to common experiences with the world, unconnected with each other or scientific knowledge. With regard to external representations, experts demonstrated the ability to identify and analyze features of external representations, transform one representation into another, generate or select appropriate representations and provide rationale, and describe the affordances and limitations of external representations. These abilities informed the formulation of representational competency that describes the symbol processing algorithms relevant to expertise in chemistry (Kozma and Russell, 2005).

Contrasting the information processing theory proposed by cognitive scientists, Jean Piaget, influence by his background in biological research, crafted his theory of knowing, Piagetian constructivism, with flavors of evolutionary biology. In his approach, the mind is treated as an active conceptual ecosystem where ideas compete and only the fittest would survive (Pugh, 2017). Although different theorists of Piagetian constructivism held slightly different views, there are common ideas accepted by all to various degrees. Most constructivists adopted an active view of the learner, and argued that instead of receiving and encoding information, the learner actively create new knowledge by interpreting personal experiences under social and cultural influence and relate the new knowledge to previously existing knowledge (Amarin & Ghishan, 2013; Sjøberg, 2010). As a result, learners would create their own individual ideas about the world that are intuitive to themselves but are often lacking in internal coherence, explanatory power, and universal applicability (Windschitl, 2002).

Under the constructivist perspective, learning is no longer a process of acquiring a copy of knowledge from outside, whether it is encoding information from the environment or acquiring better procedural rules, but a process of generating conceptual structures through actively reorganizing interpretations of personal interactions with external objects (Sjøberg, 2010; Fosnot & Perry, 1996; Amarin & Ghishan, 2013). Knowledge from an information processing perspective originates from the external world, and our mind transforms external representations in the world into internal representations in our mind, or knowledge, which may not be isomorphic to the external representation (Anderson, Reder, & Simon, 2000). In the constructivist view, however, knowledge is a mental tool invented by the learner using past experiences to reach a certain goal (Confrey, 1990). Knowledge in this perspective is no longer an internal representation transformed from external representation, but a functional mental construction invented by humans to achieve human purposes. Since human beings are living systems that seek equilibrium, knowledge is generated through accommodation and reflective abstraction to restore the equilibrium perturbed by the presence of a problem, and in turn expands the range of environments in which we can reach cognitive equilibrium (Confrey, 1991). Learning, from a Piagetian constructivist perspective, is individualized meaning-making of personal experiences. Learners enter an learning environment with an array of preconceived notions that are often at odds with canonical knowledge, but these notions are tied to prior experiences and intuitively reasonable to the learner (Sjøberg, 2010; Windschitl, 2002; Jones & Brader-Araje, 2002).

Research informed by Piagetian constructivist perspective has produced a body of literature identifying student alternative conceptions in chemistry. Rather than highlighting the differences in how experts and novice students process external information, research from a constructivist perspective focused on illustrating the differences in how students construct and communicate their internal ideas about the world. For example, Garnett et al. (1995) provided a detailed review of research on students' alternative conceptions in chemistry. The reviewed studies illustrated different student constructed concceptions in topics such as the particulate nature of matter, covalent bonding, molecules and intermolecular forces, chemical equations, chemical equilibrium, acids and bases, oxidation and reduction, and electrochemistry.

Despite differences in their theorization of learning, constructs from information processing perspective and constructivist perspective have been combined in chemistry education research on learning with external representations to characterize student conceptions and mental processes. For example, Bain et al. (2018) combined constructs from the two theoretical pespectives, namely blended processing and personal constructs, to investigate the cognitive processes involved in learning chemical kinetics. Blended processing served as a framework to characterize students' cognitive processes involved in problem solving, and personal construct served as a framework to describe knowledge as being constructed in the mind of the learner. As concepts related to chemical kinetics are often expressed through mathematical representations such as equations, tables, and graphs, the authors focused on analyzing the blended processing of chemistry and mathematics. Bain et al. conducted semi-structured interviews with students enrolled in a general chemistry course, and characterized the context, directionality, and quality of students' blending of chemsitry and mathematics when solving problems related to chemical kinetics. The cognitive perspectives of learning produced research on chemistry learning that views learning as individual activities of processing information or/and constructing conceptions.

The Social Turn of Perspectives on Learning

In chemistry education research (CER), the term "constructivism" has been used primarily in contrast to realist viewpoints and refers to any theoretical perspective that views knowledge as constructed through thought and discourse rather than derived from correspondence with external reality (Bodner, Klobuchar, & Geelan, 2001; Wink, 2014; Scerri, 2003). Scholars in CER engaged in extensive debate, with some scholars arguing for the position that only individual understandings of scientific concepts are constructed mentally. The laws of physics, on the other hand, are not socially constructed in the same sense that the laws of our society are socially constructed. To avoid the varying use of the term "constructivism" for the sake of clarity, I will refer to theoretical frameworks that focus on an individual's learning as "cognitive perspectives" and those that focus on social activities as "social perspectives".

The "social turn" of theoretical perspectives in DBER, i.e., a turn away from cognitive perspectives such as Information Processing and Piagetian Constructivism, was first observed in mathematics education, where theoretical frameworks for interpreting the social origin of knowledge began to appear in literature in 1980s (Lerman, 2000). The most distinct feature of the social turn in DBER is the consideration of meaning, thinking, and reasoning as products of social activity rather than individual activities influenced by social interactions (Lerman, 2000). Cognitive perspectives, while acknowledging the effect of the environment on individual cognition, frame learning as primarily individual activities that take place inside the learner's mind (von Glasersfeld, 1995). Social theories of learning, such as Vygotskian sociocultural theory and emergent perspective, shift the focus from inside of the learner's mind to the relationship between the learner and the environment. From a Vygotskian sociocultural perspective, the development of cognition is conceptualized as the internalization of social interactions into mental processes, and the social interactions between individuals form a basis for the cognitive development of the individual (Pugh, 2017; Walshaw, 2016). Knowledge is not just contextualized in the social environment but rather originates from the interactions between the individual and the social systems. From this perspective, knowledge is thought to exist on two planes: primarily on the social plane as different social interactions between members of a culture, and secondarily on the individual plane as mental functions derived from internalizing these social interactions (Confrey, 1995; John-Steiner, 1996).

Vygotsky saw action mediated by signs as the fundamental mechanism that links the external social world to internal human mental processes and he argued that it is "by mastering semiotically mediated processes and categories in social interaction that human consciousness is formed in the individual" (Berger, 2005). The importance of language to cognition cannot be understated. Thought and language are theorized to have different roots in their early development, but the two quickly become intertwined and melded into a unity where thought and language mutually develop each other (Vygotsky, 1986; Confrey, 1995). This unity of language and thought is the essence of human cognition and shapes the structure of our thinking. Since language is developed primarily through social interactions, cognitive skills and thinking patterns that are shaped by language also have their origin in the sociocultural environment rather than in innate factors (Schutz, 2004).

Although the idea that language mediates and shapes thought raised controversy, an increasing number of studies have published evidence to support this claim. Linguistic preference for particular spatial frame of reference has been found to be predictive of non-linguistic spatial strategies, where a linguistic preference for egocentric spatial vocabulary predicts a preference for egocentric spatial reasoning strategies (Marghetis, McComsey, & Cooperrider, 2014). The importance of spatial language is further demonstrated in a study on deaf children where researchers found that children who lack spatial vocabulary perform worse on spatial tasks than children with spatial vocabulary at their disposal (Gentner, Özyürek, Gürcanli, & Goldin-Meadow, 2013). Just as a hammer mediates driving a nail into a piece of wood, spatial vocabulary mediates spatial reasoning.

The importance of language as a mediator of cognition is also demonstrated in abstract topics such as numbers. Most of the modern world now lives in a highly quantified society where businesses are quantified in quarterly reports, student learning outcome quantified in test scores, and ownership of means of production quantified in stocks. It is almost unfathomable to a modern human that human activity can do without numbers, yet, that is the case for communities speaking the Pirahã language. Although the Pirahã has no linguistic method for expressing exact numbers, Pirahã speakers were able to perform number matching tasks perfectly (Franka, Everettb, Fedorenkoa, & Gibsona, 2008). When the matching task involves memory, however, Pirahã speakers performed poorly, indicating the role of numbers as a cultural tool for keeping track of quantities rather than a linguistic universal. The cognitive act of keeping track of exact quantities cannot be separated from the language, in this case the vocabulary of exact numbers, that mediates it.

Post-Vygotskian scholars expanded Vygotsky's theorization of language-based cultural tools that shape thinking to include nonverbal representations referred to as models (Venger, 1988). Building on the notion of models as "representations corresponding to socially elaborated patterns of sensory characteristics of objects (p. 7)", Venger (1988) proposed that the ability to generate, understand, and use models makes it possible for children to develop general cognitive competence. Models produced by learners may be abbreviated to reflect only the most essential properties of the objects they represent.

In the context of chemistry education research that focus on external representations, Vygotsky's sociocultural perspectives have informed research that sees external representations as tools that mediates meaning making. Just as well-crafted cultural tools are found to be more efficient at mediating certain cognitive activities, subpar cultural tools, on the other hand, will also impede the mediation of human cognition. For example, the diagrams used to represent the structure of organic molecules are all two dimensional, leading to the production of a common misconception that all organic molecules are flat. The limitation of certain cultural tools manifest in the act of cognition just as the advantages of certain cultural tools do, so developing a variety of cultural tools that complement each other is necessary to increase the efficacy of mediation.

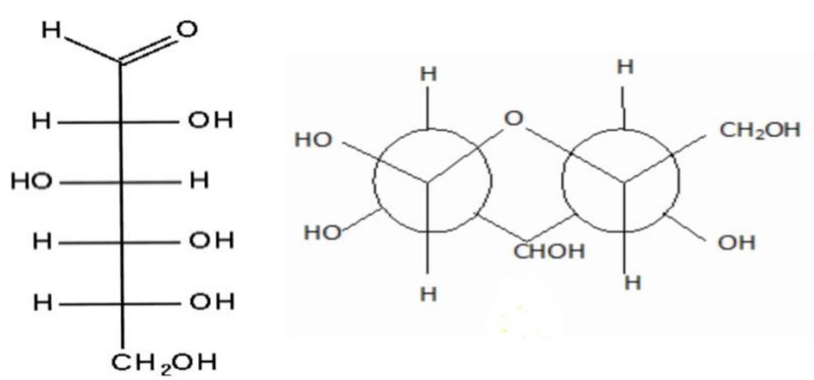

Figure 2.1: Fischer projection (left) and Newman projection (right) of glucose molecule.

For example, as shown in Figure 2.1, Fischer projections are developed by projecting a molecule onto a 2-D plane, and Newman projections are developed by projecting a molecule along a chemical bond. Although the two diagrams look vastly different, they both mediate the same activity of representing the structure of a glucose molecule. Fischer projections are commonly used to illustrate the relative position of functional groups across a molecule, since the diagram shows the molecule from a top-down perspective. However, the planar, top-down perspective adopted by a Fischer projection is not ideal for mediating the cognition of the relative positions of functional groups across a single chemical bond. Newman projections, on the other hand, are commonly used to illustrate the conformation of functional groups across a single chemical bond, since the diagram shows the molecule from a front-back perspective. The two different types of projections not only look different from each other, they also mediate different ways of engaging in the activity of representing the structure of a glucose molecule.

Central to Vygotsky's theorization of learning as internalization of social interactions mediated by cultural tools, the zone of proximal development (ZPD) is a theoretical construct that aims to help determine learners' maturing mental functions rather than their matured mental functions (Turuk, 2008; Moll, 1990). Created through the interactions between learners and more knowledgeable others, the ZPD is a symbolic space between the actual level of problem-solving ability of a learner and the learner's potential level of problem-solving ability under the guidance of an expert or in collaboration of a more capable peer (Bruce, 2003; Goos, 2004). The creation of the ZPD is essential for facilitating learning since personal knowledge is constructed in this space through the process of internalization where social interactions are transformed into mental functions (Confrey, 1995; John-Steiner, 1996; Goos, 2004). Since social interactions are the source of personal knowledge, it is pivotal to create a culture of inquiry in the classroom so that the discourse of chemistry embodied in classroom interactions can be appropriated by the students and transformed into their personal understanding. Studying different instructional practices from the perspective of ZPD creation provides insight into social interactions that establish culture. Based on different types of classroom interactions, Goos identified three methods of ZPD creation to serve as a framework for analyzing instructional practices: creating ZPD through teacher-student interaction (scaffolding), creating ZPD through student-student interaction (collaboration), and creating ZPD through concept-intuition interaction (interweaving). Although the nature of these interactions is different, actions of the teacher play an essential role in the creation of all types of ZPD, highlighting the teacher's central position in helping students internalize cultural knowledge (Goos, 2004; Taber, 2018).

The Piagetian constructivist perspective and Vygotskian sociocultural perspective each positions classroom interactions differently. In the constructivist approach, social interactions are seen as a precursor to an otherwise autonomous learning process, while in the sociocultural approach, social interactions are seen as the source of cognition. The emergent perspective attempts to coordinate the two perspectives on classroom learning by proposing a reflexive relationship between the social and the psychological, where neither can fully account for students' conceptual development as it occurs in the social context of the classroom (Cobb & Yackel, 1996). Compared to the constructivist perspective, both the emergent perspective and the sociocultural perspective recognize that social interactions do not simply perturb students' thinking and trigger their otherwise autonomous accommodation process but instead have a profound impact on their thinking and shape their cognition (Cobb & Yackel, 1996). However, the emergent perspective focuses on the participation in a local community such as a classroom while the sociocultural perspective focuses on the participation in a broader sociocultural practice. For example, from the emergent perspective, all sociological constructs that model classroom interaction have their corresponding psychological constructs that model student thinking. In the context of CER, students' beliefs about their own role, others' roles, and the general nature of activities related to chemistry in formal classroom instruction are theorized to correspond to the classroom social norms; beliefs and values about chemistry are theorized to correspond to classroom sociochemical norms; and chemical conceptions and activities are theorized to correspond to classroom chemical practices (Cobb & Yackel, 1996).

The different emphases of the emergent perspective and the sociocultural perspective also result in different characterization of the teacher's role in classroom discourse (Cobb & Yackel, 1996). In the sociocultural perspective, the teacher is characterized as an expert in a culture of practice who scaffolds students' learning by pushing them forward in their zones of proximal development toward culturally accepted ideas. In the emergent perspective, however, the teacher's role is characterized as supporting the students' individual construction of meaning and guiding the evolution of classroom practice. Rather than using the broader society as the point of reference, the emergent perspective adopts the local classroom as the point of reference, and frames instruction as the emergence of individual and community meanings in the classroom.

The Ontological Turn of Perspectives on Learning

In recent years, an increasing number of education scholars from various subfields of educational research started calling for an ontological turn to shift focus to the question of who students become rather than what they have learned (Brown, 2009; Dall'Alba & Barnacle, 2007; Zembylas, 2017). The turn towards investigating identity has led to the increased relevance of identity theoretical frameworks. For example, Gee (2000) proposed a framework of identity as a third person descriptor. An individual's identity is theorized as a collection of characteristics and details that are recognized by others. Gee (2000) defined four types of identity: Nature Identity, Institution Identity, Discourse Identity, and Affinity-Identity. Nature identities are fixed characteristics developed from biology. Institution identities are authorized characteristics that are produced by, and producers of, social structures. Discourse identities are designated characteristics resulting from shared meanings. And lastly, Affinity identities are experienced characteristics through the practices in which an individual took part.

Building on Gee's Discourse Identity, Brown, Reveles, and Kelly (2005) developed the notion of a discursive identity. Discursive identity reflects how individuals use their understanding of, and participation in, discourse in order to position their own identity or interpret others' identities. Brown and colleagues described that "an individual may select genres of discourse or avoid specific genres of discourse in an effort to be seen as a particular type of person" (Brown et al., 2005, p. 789). While Discourse identity is about the identities that come into play through interaction, discursive identity describes the agency that individuals have to engage in, or veer away from, the discourse that promotes a certain identity. For example, an individual may use slang or jargon associated with a certain group in order to be seen as a member. Brown and colleagues used the example of a student who might want to be considered an "activist", during their interactions with others they might use legal, environmental, or scientific jargon and/or actively avoid using language that might make them appear racist, careless, or other attributes that they perceive as antithetical to their identity as an activist.

As a critique of Gee's definition of identity, Sfard and Prusak (2005) argued that identity should be theorized as the narratives surrounding an individual. The approach of narrative identities accounts for the contingent nature of human identities and contextualizes identity research as the study of the discourses surrounding an individual. Narrative identity framework theorizes that a sense of identity, the belief that a person belongs to a certain identity label or community, is the outcome of discourse. To further illustrate the notion of narrative identities, Sfard and Prusak (2005) proposed two subcategories of identity: actual identities and designated identities. Actual identities are defined in a straight-forward manner as stories that depict the current state. Statements about actual identities are usually described using the "is" verb, occur in the present tense, and are formulated as factual assertions such as "I am an army official". In contrast, designated identities "are stories believed to have the potential to become a part of one's actual identity" (Sfard & Prusak, 2005, p. 18). Designated identities are usually described using "should", "ought", "have to", "must", "want", "can", and "cannot" verbs and occur in the future tense. The actions of an individual may align with how they perceive themselves to be, regardless of whether the designated identities are factual. These designated identities may stem from the unconscious absorption of dialogues perfused in the immediate environment or from an individual's attraction to certain people and the internalization of those people's characteristics. Designated identities can play a significant role in determining a learner's academic outcome. Sfard and Prusak (2005) argue that learners given the same resources would only be relatively limited by their own perspectives of who they can or cannot be. Thus, the formation of designated identities produces varying academic performances from students within the same classroom.

In chemistry education research, chemistry identity has been researched from the perspective of being recognized as a chemistry person in the classroom. With physics identity framework as a starting point, Hosbein and Barbera (2020) conducted a thematic analysis of student responses in an interview pertaining to chemistry identity, and identified emerging themes that align with theoretical constructs. A total of four themes were identified: 1) interest in chemistry is based on feelings or values and occurs in stages, 2) educational experiences contribute to student chemistry identity, 3) students gain information about identity through interactions with others, 4) participation in chemistry takes a certain type of person. Hosbein and Barbera then align these themes with affective constructs such as situational interest, mastery experiences, verbal persuasion, vicarious experience, and mindset to develop and evaluate a new measurement tool for student chemistry identity (Hosbein & Barbera, 2020). The theoretical consideration of identity formation expanded chemistry education research to include research on chemistry identity. Although the theoretical perspectives discussed thus far produced a variety of approaches to conducting CER, they share a set of philosophical assumptions. In the next section, I will discuss three shared philosophical assumptions to provide a context and a starting point to explore theoretical considerations that can explore possibilities for new approaches to conducting CER.

Philosophical Assumptions of Theoretical Frameworks

> Gazing out into the night sky or deep down into the structure of matter, with telescope or microscope in hand, Man reconfirms his ability to negotiate immense differences in scale in the blink of an eye. Designed specifically for our visual apparatus, telescopes and microscopes are the stuff of mirrors, reflecting what is out there. Nothing is too vast or too minute. Though a mere speck, a blip on the radar screen of all that is, Man is an individual apart from all the rest. And it is this very distinction that bestows on him the inheritance of distance, a place from which to reflect—on the world, his fellow man, and himself. A distinct individual, the unit of all measure, finite due made flesh, his separateness is key. – Barad, Meeting the Universe Halfway, 2007, p. 134

The theoretical perspectives described above serve to provide context for the philosophical assumptions discussed in this section. Previously, I focused on illustrating the differences among the ways that scholars have theorized learning. Research guided by different theoretical perspectives often produces different knowledge claims about the learner. However, despite their differences, these theoretical frameworks share a worldview described by Barad in the above quote. Representationalism, metaphysical individualism, and humanism work together to hold this worldview in place. These philosophical assumptions are commonly associated with classical ontology, which entails a physical reality underpinned by objectively real, counterfactually definite, uniquely spatiotemporally defined, local, dynamical entities with determinately valued properties (Evans, 2020). In addition to separating physical reality into uniquely bounded entities, classical ontology also separates mind and matter, creating two disjunct domains for words and things, respectively. In research, these philosophical assumptions limit the possible relationships between data and the analysis of data (Koro-Ljungberg, 2015). Knowledge production that operationalizes this ontology seeks to create accurate and authentic representations through measuring the determinately valued properties of the bounded entities. In this section, I will discuss the often-implicit shared assumptions of representationalism, metaphysical individualism, and humanism in the theoretical frameworks reviewed above and some limitations of committing to these assumptions.

Representationalism

Representationalism, the view that scientific models are best understood as representations of reality, is common in discipline-based science education. Representationalism separates epistemology from ontology, treats the words that we use to describe knowledge and the things of which we have knowledge as belonging to disjunct domains, and leads to the question of mediation between the two realms that made knowledge possible. Sharing the commitment to representationalism, the theoretical frameworks reviewed above provide various answers to the question of mediation. The information processing perspective's answer is simple: the human mind directly encodes information from external world into symbols. The referentiality of words is transparent, and there is a direct correspondence with external reality.

Piagetian constructivism assumes the same separation as the information processing perspective but reverses the flow of information. Rather than encoding information received from outside, the mind constructs its own internal representation to fit environmental factors. The question of mediation in constructivism is tackled with the construct of assimilation. Social perspectives, however, reframe the question of mediation to focus on the mediation between social activity and individual mental processes, rather than the mediation between an external physical world and individual minds. However, this move only replaces the physical reality with a social one. The externality of this reality is still intact. Despite taking different epistemological stances and proposing different mechanisms for learning, cognitive perspectives and social perspectives agree that there is a reality, whether material or social, that is "out there", and that we use language/signs to represent this reality "internally".

Scholars have voiced their concerns about the limitation of the binary notion that nature and language are oppositional ontological categories. Barad criticized this binary notion for trapping epistemology between two facing mirrors of scientific realism and social constructivism where it "gets bounced back and forth, but nothing more is seen" (Barad, 2003, p. 803). Matter and meaning may not have direct correspondence with each other; however, the two are entangled as parts of the broader process of material-semiotic worlding, i.e., the process through which nature and culture are iteratively and reflexively produced and reproduced. If we commit to the assumption that cognition involves a separated cognitive subject representing an external object, the study of cognition itself would require another degree of separation, i.e., meta-cognition. To investigate meta-cognition and gain insight on the process through which the cognitive subject reflects on its own cognition as an object, another degree of separation would then be needed, so meta-meta-cognition must be considered, and so on. Cognition viewed through representationalism is about producing a mirror image, so the cognitive subject is viewed as a mirror reflecting an external reality. Studying cognition under this assumption is akin to placing two mirrors against each other. We become trapped in between two reflective surfaces, bouncing back and forth.

The commitment to representationalism has implications for conducting critical research as well. Higgins (2021) questions the taken-for-granted ways-of-critiquing in science education and explores the possibility of critique as plural where "the" critical attitude is but "a" critical attitude. The author draws on Latour's (2004) critique of critique, suggesting that most critical efforts employ the same mode of critique by positioning the object of inquiry, whether concrete or conceptual, in one of two positions: good representation of reality (fact) or bad representation of reality (fiction). The critics themselves act as a mirror of the observed phenomena by giving the accurate representation of reality. For example, a critic of education can argue that framing pedagogy as scaffold for learning is a bad reflection of reality. Instead, pedagogy is brought in to sanction the failure of internalization of a cultural arbitrary (e.g., the cultural values and preferences of scientists) (Bourdieu & Passeron, 1990; Borg & Mayo, 2001). Individuals who can readily and successfully internalize a cultural arbitrary are deemed as "talented" or "gifted", while individuals who resist the imposition of a cultural arbitrary are prescribed more pedagogy. Research serves to advance the capability and precision of sanctions, so various types of failures can be readily identified and appropriately sanctioned to provide a higher yield of successful internalization. The "fiction" of pedagogy as scaffolding personal learning is explained by the "fact" of pedagogy as imposing the culture of a community. Operationalizing the mode of critique underpinned by representationalism invites those who disagree to critique the argument similarly by reversing the positions of "fact" and "fiction". One can argue that the belief of pedagogy as sanction for failure of internalization is a “fiction”, while the “fact” is that those arguments are politically motivated (Higgins, 2021). Therefore, subscribing to representationalism can lead the discourse of debate to a standstill, locked in ongoing dialectic reversal.

Metaphysical Individualism

The metaphysics of individually determinate entities with inherent properties is another fundamental assumption on which many scientific, social, political, and ethical practices are hinged. DBER, like other fields of educational research, are commonly shaped by the ideal of putting the individual student at the center of attention. In the theoretical perspectives reviewed above, the primary ontological unit is pre-existing entities with independently determinate boundaries and properties. Assuming individual students are determinately bounded entities entails properties that can differentiate and describe individuals. From the information processing perspective, each individual person is a determinately bounded information processing system with pre-existing properties and internal algorithms that can be accurately measured by performance outcomes. For Piagetian constructivism, each individual person is an agent who seeks equilibrium and adapts to the environment. Although social perspectives turn towards social activities rather than individual cognitive activities, social activities are theorized as interactions between determinately bounded individuals. For example, the zone of proximal development (ZPD) is a central construct in Vygotskian sociocultural perspective of learning, and it is theorized as a symbolic space between the actual level of problem-solving ability of a learner and the learner’s potential level of problem-solving ability under the guidance of an expert or in collaboration of a more capable peer (Goos, 2004). The ZPD assumes that there is a determinately bounded individual with some level of “actual” problem solving ability before they enter social interactions with others.

The outside boundary of a body, whether a human or nonhuman body, may seem self-evident at first glance. Our visual cues suggest that a basketball ends at its surface just as surely as an individual ends at their skin. However, scholars from a range of disciplines such as neurophysiology, anthropology, physics, feminism, and disability studies have called into question the self-evidentiary nature of bodily boundaries. For example, Richard Feynman questioned the givenness of an object’s outline and argued that bodily boundaries are enacted by human psychology (Feynman, 1964). Physically, the boundaries of objects are not determinate, and the edges are not as sharp as we may assume. When a player holds a basketball, there is not a sharp line that separates the atoms that belong to the basketball and the atoms that belong to the player’s hand. Undermining the taken-for-granted distinction between inside and outside of an individual person, Maurice Merleau-Ponty argued that the successful performance of a task depends on both the incorporation of the tool into the body as well as the dilation of our being into the tool. To get used to dribbling a basketball or focusing a microscope is “to be transplanted into them, or conversely, to incorporate them into the bulk of our own body” (Merleau-Ponty, 1962). Disability scholars have also pointed out that the luxury of taking for granted the nature of the body is enabled by privileges of ableism: “able-bodiedness” is not a natural state of being but a specific form of embodiment to exclude “disabled” from “able-bodied” (Diedrich, 2001). Donna Haraway echoed that we need “the kind of standpoint with stakes in showing how ‘gender,’ ‘race,’ or any structured inequality in each interlocking specific instance gets built into the world—i.e., not ‘gender’ or ‘race’ as attributes or as properties, but ‘racialized gender’ as a practice that builds worlds and objects in some way rather than others, that gets built into objects and practices and exists in no other way. Bodies in the making, not bodies made" (Haraway, 1991, p195). What it means for a body to be gendered, sexed, racialized, or otherwise labeled is always in a state of becoming with surrounding entities. Therefore, student achievement, skill competence, race, gender, and disability can no longer be seen as individual affairs that can be measured to describe some facts about individual students.

Humanism

Another assumption that is closely related to representationalism and metaphysical individualism is humanism, which assumes a separated position of the human subjectivity to reflect on nonhuman nature at a distance, and attributes agency to only the human side of this separation. For some, a human-independent nature is a condition for science to be possible (Habermas, 1971). Science "works" because it is uncovering facts about a human-independent nature. Nature is revealed/modeled by, yet independent of, the theoretical and experimental practices of science. The information processing perspective and Piagetian constructivism may disagree on whether the human knower is receiving information directly from nature or constructing a model to fit nature; however, both perspectives acknowledge that there is a passive, human-independent nature and a human knower with agency.

With the separation of the human and the nonhuman taken for granted as a foundational philosophical assumption, current discipline-based education research focuses on conceptual understanding and identity in mutually exclusive research practices, with different frameworks for each focus. Learning outcomes are often reduced to measurable competency and economically exploitable skills. Identities and agency are compartmentalized as different "human factors" in an impersonal and fundamentally inhuman process of producing labor, without consideration of the formation of the whole human being and the question of what it means to be human (Zovko & Dillon, 2018). Separating humans as exceptions from the "nonhuman nature" ironically works instead to dehumanize the human subject instead.

Critically reflecting on the philosophical assumptions of DBER is not intended to accuse research under these assumptions of producing an inaccurate representation of "reality". Doing so would be committing to representationalism once again. Instead, the point is to illustrate the power of philosophical assumptions in enacting boundaries that produce specific kinds of subject-object relationships that are sensible. All theorizations of learning are based on fundamental philosophical assumptions about the world, knowledge, and their relations. In the next section, I will discuss agential realism, an onto-epistemological framework that moves beyond the current normative worldview upheld by representationalism, metaphysical individualism, and humanism.

Agential Realism

> What we need is to make a difference in material-semiotic apparatuses, to diffract the rays of technoscience so that we get more promising interference patterns on the recording films of our lives and bodies – Donna Haraway, 1997, Modest_Witness@Second_Millennium.FemaleMan©_Meets_OncoMouse™, p. 16

Proposed by theoretical physicist and feminist theorist Karen Barad, agential realism is an ethico-onto-epistemology (as Barad argued that ethics, ontology, and epistemology are all entangled) that acknowledges the dynamism of material and advocates for "a relationality between specific material (re)configurings of the world through which boundaries, properties, meanings are differentially enacted and specific material phenomena" (Barad, 2007, p135). One goal of agential realism is to think the social and the natural together without defining one against the other or privileging either nature or culture as the primary referent from which the other is to be understood. Agential realism departs from classical ontology by rejecting the assumption that the world comes in already divided pre-existing substances carrying out predetermined inherent properties that can be transparently measured from a distance. In light of developments in quantum physics, feminist theory, philosophy, and science studies, the worldview held up by classical ontology is being extensively challenged and thinking with classical ontology is becoming increasingly untenable. Engaging with agential realism is a venture into research spaces where classical ontology becomes seriously unthinkable, in the sense that it becomes unavailable to think-with.

The disembodied doctrine of objectivity prevalent in science textbooks has been thoroughly challenged by social studies of science, which made strong arguments that textbook ideologies about objectivity and scientific method are far from how scientific knowledge is actually made (Haraway, 1988). From the social constructivist perspective, science is often reduced to argumentation and the practice of persuasion. The nature of truth is rhetorical, and any drawings of expert-novice boundaries in knowledge are theorized as power moves. While such a position is tempting given the body of literature that showed the historical specificity, and, therefore, contestability, of scientific constructions, committing to the rhetorical nature of science does not sit well with scholars who wish to talk about reality with more confidence than we allow to conspiracy theorists when they talk about the "illuminati". Believing something to be true, no matter by how many people, does not make it true. Humans are not the sole authority of truth, and natural scientists are familiar with how nature pushes back against our rhetoric (e.g., the experiment proposed by Poisson to disprove the wave theory of light ended up producing the Poisson's spot that supported the theory). Habermas (1971) argued that a human-independent nature is itself a human ideal:

> While epistemologically we must presuppose nature as existing in itself, we ourselves have access to nature only within the historical dimension disclosed by labor processes. Here nature in human form mediates itself with objective nature, the ground and environment of the human world. 'Nature in itself' is therefore an

> abstraction, which is a requisite of our thought: but we always encounter nature within the horizon of the world-historical self-formative process of mankind - Habermas, 1971, Knowledge and Human Interests, p. 33.

All materiality is socially, historically, culturally, and politically constructed; and likewise, the social, historical, cultural, and political realities are physically constructed. Therefore, realism needs to be reformulated to do without some imagined and idealized human-independent reality and account for agential reality—reality within which we intra-act as a part within it rather than interact as separated from it.

Agential realism rejects both naïve empiricism of the positivistic obsession with objective knowledge as well as the thoroughgoing relativism that views all knowledges as equivalent, while taking account of the conditions under which knowledge is generated and defended. When people and things are no longer viewed as having determinate inherent properties, we must look to relations and practices to understand the processes through which identities are attributed to people and things (Østerlund, Crowston, & Jackson, 2020). In this sense, agential realism challenges the reductive over-organization that renders the individual as nothing more than an accumulation of identity labels. All of life is in a process of becoming that happens at different tempos, in different rhythms, and leaves different impressions. Both human and nonhuman partners are entangled in this process and act of becoming. In Figure 2.2 below, the relationship between the various theoretical constructs in agential realism is shown.

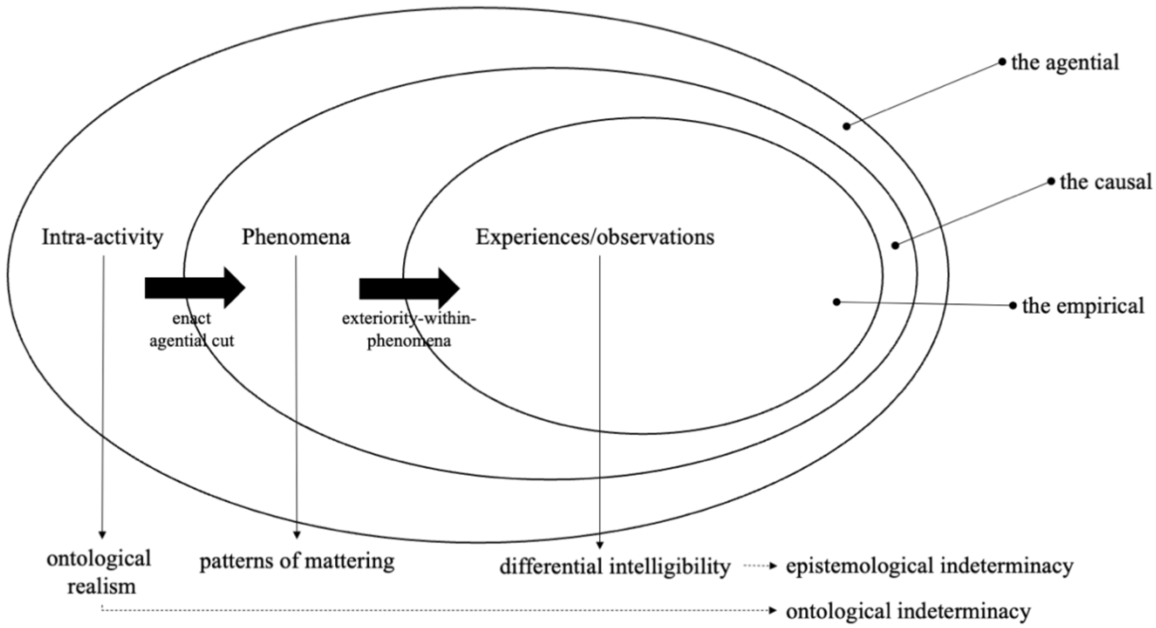

Figure 2.2: Illustration of agential realism.

The most fundamental ontological unit in agential realism is intra-activity, or relations without relata. The ontological indeterminacy of the world stems from the ongoing dynamic (re)configuration of intra-activity. Through intra-action, phenomena are enacted, and boundaries within phenomena are drawn to separate experiences and what is being experienced. To further illustrate the central tenets of agential realism, I will discuss three central constructs—phenomenon, intra-activity, and agency—that provide alternatives to the assumptions of representationalism, metaphysical individualism, and humanism.

Phenomenon

> …phenomena are differential patterns of mattering produced through complex agential intra-actions of multiple material-discursive practices…it is through such practices that the differential boundaries between humans and nonhumans, culture and nature, science and the social, are constituted…The world is a dynamic process of intra-activity and materialization in the enactment of determinate causal structures with determinate boundaries, properties, meanings, and patterns of marks on bodies. -- Barad, 2007, p140

One central philosophical stance of agential realism is to challenge the assumption that realism entails a commitment to representationalism and individualist metaphysics. “Realness does not necessarily imply ‘thingness’: what’s real may not be an essence, an entity, or an independently existing object with inherent attributes” (Barad, 2007, p. 56). Phenomenon (in the agential realist sense described below) replaces object as the primary ontological unit in agential realism. Reality is not made of things or things-behind-phenomenon, but rather things-in-phenomenon. Phenomena are primitive relations, i.e., relations without relata. Positing phenomenon as the primary ontological unit instead of things means that the central issue with measurement is not about the disturbance that measurement may or may not have on an otherwise closed system being measured, but about resolving an inherent indeterminacy within a phenomenon. In other words, phenomenon is a single situation where “objects” and “agencies of observation” cannot be abstracted out as representations of independently pre-existing entities; both must be understood as parts of what is being described. Therefore, measured values in observation cannot be seen either as attributes of an abstract observation-independent object or as created by the act of measurement. As measurement practices are an ineliminable part of measured values, these values refer to phenomena rather than objects.

Rejecting a metaphysics of objects with inherent properties, the agential realist account of scientific practices does not involve discovering facts about an independent pre-existing world; instead, what is produced is “the effect of the intra-active engagement of our participation with/in and as part of the world’s differential becoming” (Barad, 2007, p. 361). Phenomena, including our “minds”, are real material beings that emerge through specific intra-action. Technological and scientific practices together enact specific material resolutions and manifest an expression of the objective existence of material phenomena. Focusing on phenomena rather than individual objects/subjects reworks what it means to be "human", "minority", "high performing", "able-bodied", etc. The nature of being is to live as part of a phenomenon that includes what is excluded and the boundary for exclusion. Therefore, objectivity in an agential realist sense must also encompass a genealogical accounting of the full set of practices that is a part of the phenomenon investigated or produced, including "the enactment of boundaries, the production of phenomena in their sedimenting historiality, and the ongoing reconfiguring of the space of possibilities for future enactments" (Barad, 2007, p. 391).

Donna Haraway illustrated the coproduction of nature-culture in technological and scientific practices with the example of the production of species as a phenomenon. In the laboratory, the seemingly natural differences among species are made intelligible in boundary-drawing research practices. The different species are not simply labels that refer to creatures in the world since the production of each label requires a set of technological and scientific practices of articulating its difference from other labels. Therefore, the discovery of a new species entails a phenomenon where boundaries that separate biological creatures are differently constituted. Haraway argues that nature is both a natural-cultural matter and a "situated knowledge" because it is produced by specific actors (human or nonhuman), in specific times, and in specific places (Haraway, 1988). Barad (2003, 2007) extends Haraway's argument and emphasizes the importance of considering all the material-discursive practices that draw boundaries and produce scientific findings.

Intra-activity

> On an agential realist account, causal relations cannot be thought of as specific relations between isolated objects; rather causal relations necessarily entail a specification of the material apparatus that enacts an agential cut between determinately bounded and propertied entities within a phenomenon… The marks left on the agencies of observation (the effect) are said to constitute a measurement of specific features of the object (the cause). In a scientific context,

> this process is known as a measurement. (Indeed, the notion of measurement is nothing more or less than a causal intra-action). Whether it is thought of as a measurement, or as part of the universe making itself intelligible to another part in its ongoing differentiating intelligibility and materialization, is a matter of preference. – Barad, 2007, p176

Intra-action is a term introduced by Barad to signify agential realism's departure from a worldview where pre-existing objects interact with each other. Replacing objects with phenomena as the fundamental ontological unit implies that matter is a dynamic expression/articulation of the world rather than passive material waiting to be shaped. The iterative intra-activity of the world is the process through which all bodies, human and nonhuman alike, come to matter; it is the world's performativity. Intra-activities are "nonarbitrary, nondeterministic causal enactments through which matter-in-the-process-of-becoming is iteratively enfolded into its ongoing differential materialization" (Barad, 2007, p. 179).

Positing a relational ontology means that concepts such as "tools" and "objects" are relational, i.e., their meaning/mattering are a result of, and as a part of, the dynamic and contingent ongoing intra-activity of the world that differentiates itself into specific relationalities. For example, a white cane is a device often used by blind folks to scan their surroundings. There are two mutually exclusive patterns of intra-activity: a person can hold the cane loosely and feel the texture, length, thickness, etc., of the cane, or they can hold the cane firmly to feel the surrounding, but not both at the same time. The different intra-activities enact the boundary of the subject differently. When the cane is being held loosely, the boundary of the subject is at the fingertip. When the cane is being held firmly, the boundary of the subject is at the tip of the cane. Therefore, the intra-action where a person is holding the cane loosely constitutes the cane as an object, while the intra-action where a person is holding the cane firmly constitutes the cane as a tool. Similarly, a scanning electron microscope shares these patterns of intra-activity with white cane, being both an artifact of engineering and a tool for science. Just as we cannot hold the cane loosely and firmly at the same time, we cannot troubleshoot the microscope and use it at the same time. The same applies to our semiotic tools as well. A representation cannot both refer to the thing it represents and be an object in itself simultaneously; and we cannot think about something and think about our thoughts about that thing at the same time. The boundary between subject and object is not absolute and does not pre-exist the practice of their engagement, but neither is it arbitrary. The boundary between subject and object emerges through and as part of the specific material-semiotic practices that are enacted. Subjectivity is therefore not a matter of the individual, but "a relation of responsibility to the other" (Barad, 2007, p 391).

Using a white cane as an example shifted our metaphor for knowing from seeing to touching, but the relation between knower and known is much more intimate. Replacing representationalism with a performative alternative shifts the focus of objectivity from "questions of correspondence between descriptions and reality to matters of practices, doings, and actions" (Barad, 2007, p. 135). Without the absolute separation between subject and object, objectivity is no longer about holding a position of the enlightened outsider, but "a matter of accountability for what materializes, for what comes to be" (Barad, 2007, p. 361). Objectivity is being accountable for the cuts that are being enacted as different cuts enact different materialized becomings. Rather than merely producing different representations of an independent external reality, a different material-discursive apparatus of bodily production materializes a different configuration of the world. If problem solving can be learning through engaging in problem-solving activities, students should be different after completing an assessment, just as the assessment instrument become different with marks left by the students. We are responsible for the world not because we "created" a world arbitrarily according to our intentions, but because the world is sedimented out of the entangled practices that we have a role in shaping and through which we are shaped. Barad (2007) wrote: "'Now' is not an infinitesimal slice but an infinitely rich condensed node in a changing field diffracted across spacetime in its ongoing iterative repatterning." Without the assumption of a pre-existing reality waiting for interaction with a pre-existing subject, observations and measurements cannot be treated as "snapshots" of reality. Rather, they are intersections of intra-activity in world's ongoing iterative becoming.

Agency

> In summary, the primary ontological unites are not "things" but phenomena – dynamic topological reconfigurings/entanglements/relationalities/(re)articulations of the world. And the primary semantic unites are not "words" but material-discursive practices through which (ontic and semantic) boundaries are constituted. This dynamism is agency. Agency is not an attribute but the ongoing reconfigurings of the world. The universe is agential intra-activity in its becoming. – Barad, 2007, p141

As part of the move towards posthuman performative perspectives, agency is rethought as an enactment rather than an attribute. Disentangling agency and humanism means conceptualizing a larger space of agency where agency is not something unique to humans and matter is agential in its iterative materialization. The core issue about agency is not the location or distribution of it, but the possibilities of the iterative reconfiguration of materiality. Holding the category "human" as a fixed category excludes possibilities of existence in advance. Agential realism relocates the notion of agency from humans to complex assemblages of both human and nonhuman agents. Thinking about agency in this sense challenges the idea that the separation of humans from the material world is required for knowledge production and reinstates the material as partners with humans in the production process. The question of agency is therefore about the forces that held together/apart bricolages of human and nonhuman agents. It is about the "changing possibilities of change entailed in reconfiguring material-discursive apparatuses of bodily production, including the boundary articulations and exclusions that are marked by this practice in the enactment of a causal structure" (Barad, 2007, p. 230). Possibilities for intra-acting are present and changing at every moment, and agency is about the changing possibilities rather than about an attribute that someone or something has.

For example, Hogan (2008) presented a case study on a Yup'ik middle schooler, Nora, to explore the micro- and macropolitical contexts of school reform. Although Hogan did not engage with agential realism, the insights presented in this study can help illustrate the posthuman perspective of agency conceptualized in agential realism. When moving from 6^{th} grade to 7^{th} grade and shifting from a culturally relevant curriculum to a curriculum typical in a Western-style classroom, Nora was very differently constructed as a math learner by her teachers. With a culturally relevant curriculum, Nora was confident and collaborative. With a Western-style curriculum, however, Nora was much less vocal and worked almost exclusively alone. The two Nora's show that student subjectivity emerges from the intra-actions as a part of the material-discursive assemblages of school mathematics. In the agential realist sense, agency is not something that Nora had but then lost or got taken away; agency is relational. Changes in the material-discursive assemblage produce the agency that reconfigures what is possible and impossible. Agency is about what was possible for Nora and school mathematics.

Chapter 3: Agential Variation Theory

In the context of science education, unmasking the doctrines of objectivity by showing the historicity of scientific and technological constructions was intended to create space for our sense of collective historical subjectivity and our embodied accounts of truth, rather than to provide an excuse to dismiss laws of physics as merely texts and molecular models as merely cartoons. Therefore, as Haraway (1988) pointed out, for scholars who wish to hold on to a notion of objectivity, the task at hand is "to have simultaneously an account of radical historical contingency for all knowledge claims and knowing subjects, a critical practice for recognizing our own 'semiotic technologies' for making meanings, and a no-nonsense commitment to a faithful account of a 'real' world" (p. 579). Stetsenko (2008) expressed concern about the divide in education research where research from sociocultural perspectives and research from cognitivist perspectives remained starkly disconnected, without much dialogue nor coordination among them.

For example, chemistry education scholars have theorized that chemistry knowledge can be roughly divided into the macroscopic, the microscopic, and the symbolic (Johnstone, 2000). The meaning of symbolic knowledge is argued to originate from its correspondence with the microscopic and macroscopic knowledge, i.e., the meaning of chemical symbols originates from their referentiality to microscopic and macroscopic entities and phenomenon. Science studies scholars, on the other hand, have argued that science is not merely a body of knowledge or a collection of experiments; it is part of a complexly entangled set of practices that include scientific, technological, social, economic, medical, and cultural apparatuses of bodily production (Haraway, 1988; Barad, 2007). From this view, the macroscopic, the microscopic, and the symbolic are not three realms of knowledge that correspond with each other, but all parts of the technoscientific practices that constitute chemists' way of intra-acting as part of the world. Adding to the complex theorization about science, knowledge, and learning, practice has also been theorized extensively by social science scholars. For Wenger (1999), practice is activities shared within a community. Community and practice mutually constitute each other. Thus, the notion of practice is tied to local communities, while discourses of broader institutions, such as that of science, "connect the practices of different communities where they find realizations that may or may not be congruent" (p. 133). For Bourdieu, practice is where subjective experience meets objective reality (Bourdieu & Passeron, 1990). Pedagogy works to inculcate durable, transposable habitus capable of generating practices. Pedagogical work produces both the legitimate learning object worthy to be consumed as well as the legitimate subject with a propensity to consume this object. In both perspectives, practice is the object of learning/pedagogy.

To address this disconnection, science education scholars drew on new materialism(s), such as agential realism, to help rethink science education research and justice-oriented science learning and teaching (Bazzul, Tolbert, & Kayumova, 2019; Haus & Siry, 2019; Morabito, 2019). In chemistry education research, the engagement with new materialism has primarily been in the context of laboratory instruction to examine the role of instruments and chemicals, while such engagement remains rare in research on external representations (Milne, 2019; Wink, 2020). Thus, the broad rationale for developing agential variation theory is the need for a better integration, or at least coordination, of the insights from various disciplines including cognitive science, science studies, education, and feminism to produce a nuanced analysis of chemistry student learning with external representation through bridging the various areas of research related to learning and representation. In this chapter, I will propose agential variation theory by drawing on agential realism, variation theory, and sociocultural perspective to build a post-humanist, performative account of learning and problem-solving with external representation in chemistry. Before I discuss the central theoretical considerations of agential variation theory, I will first present some philosophical discussion about knowledge and meaning.

Meaning and Identity

What does a flower know about being a flower? On one hand, being a flower is the complete embodiment of the identity of a flower. On the other hand, asking a flower to explain photosynthesis or to take a flower anatomy concept inventory test can produce the result that a flower does not know the first thing about being a flower. What does a computer know about being a flower? Searching quickly through a database can produce a plethora of representations of flower anatomy and explanations for photosynthesis, but a computer can never experience blossoming. Wenger (1997) argued that neither a flower nor a computer is capable of experiencing meaning, as a flower cannot make sense of the linguistic reifications that are intrinsic to our knowledge practices, and a computer lacks an identity of participation with which to take responsibility for meaning. In the context of biochemistry learning, when a student is learning about the biochemical processes of the human body, such as the facilitation of GTP hydrolysis by G-proteins, what the student is learning is already embodied by the student – the hydrolysis of GTP is happening as part of the student's physical existence. But the embodiment of the GTP hydrolysis does not mean that the student can explain it scientifically. On the other hand, online databases contain a plethora of information about the hydrolysis of GTP, but these databases cannot experience the meaning of the information that they store as chemists. The materiality and the semiotics of knowledge cannot be separated and considered in isolation. Meaning and matter are entangled in their mutual articulation.

How can meaning be experienced? In variation theory, it is proposed that meaning arise from experiencing variation in the world. Marton and Booth (1997) used the everyday example of color to illustrate this point: if everything in the world is the same color, then the phenomenon of color cannot be experienced, as one color can only be experienced in contrast to another. Building on the insight that variation is necessary for meaning making, variation theory suggests that students construct their understanding of representations from discerning the variation of critical features (Bussey, Orgill, & Crippen, 2013; Bussey & Orgill, 2015). For example, to understand the representation of a ripe banana, one must discern critical features associated with ripeness, such as color. Discerning the color associated with ripeness would require experiencing the variation of color between under-ripe, ripe, and over-ripe bananas. In addition, the possible colors of bananas must also be contrasted with colors that are impossible for bananas to discern bananas from other objects (e.g., a blue banana-shaped object would not be immediately understood as a real banana, so ripeness would not apply). Questioning the referentiality of representations means that ripeness may not simply refer to the features of bananas as objects. If we also challenge the apparent "thingness" of the world, there may not be a banana as a pre-existing object to be represented by a pre-existing subject.

Although Marton's argument mainly pertains to the material world, it resonates with Derrida's work on the relationship between text and meaning that is commonly associated with post-structuralism. For Derrida (1974), "language works not because there is an identity between a sign and a thing, not because of presence, but because there is a difference, an absence". In other words, the meaning of a sign derives from its variation from other signs. Material-semiotic variations enact boundaries within a phenomenon, through which the critical aspects of a phenomenon become bounded and propertied, and the meaning of an experience of the phenomenon emerges. When we think about the concepts in chemistry, the meaning of these concepts derives not from their correspondence to physical entities, or an identity, but from their variation to other concepts and the variation between physical entities. For example, the term "acid" has held various meanings in the history of chemistry. Arrhenius acids, Bronsted-Lowry acid, and Lewis acid all define the meaning of acid differently. All the various definitions of acid are accompanied and contrasted with a definition of base. The meaning of acid and the meaning of base are mutually constitutive; a new definition of acid is always associated with a new definition of base. The variation between the different definitions of acid and base is resulted from the different intra-actions through which matter and meaning are constituted.

In addition, the development of these new concepts is connected with the technological advances that made it possible to not only have linguistic definitions of concepts but also material definitions. The perspective of technoscience positions science as a practice of knowing and acting (Chamizo, 2013). From this view, analysis as a knowledge practice may be associated with the technical practice of rationalization particularly of manufacturing production. In general, substances are the aim and the results of the most important experimental practices in chemistry. To this aim, two knowledge practices, analysis and synthesis, are regarded as most central to chemistry. The term technoscience describes the practice through which chemists rationalize, invent, and intervene in the world to produce new forms of matter. It is a way of knowing and a way of making. The intertwined nature of rationalization and production in chemistry can also be noted in the notion that chemical processes produce matter that is "artificial", excluded from those that are deemed as "natural", which simply "exists" in nature. The main way that chemists know is by doing and their actions increases the complexity of the world.

An important practice of chemistry is the use of representations. The ball and stick model not only allowed chemists to analyze the spatial arrangement of atoms in a compound, but also pointed towards the possibilities of synthesizing new compounds: if you could represent natural compounds, you can extend your representations to novel compounds as targets for synthesis. The combination of atomic and molecular models encouraged efforts to build new molecules. The material-discursive and analytical-synthetic nature of representational practices is the focus of investigation for agential variation theory. From the agential variation theory perspective, symbols are not separated from the material, and concepts are not ideational in nature. The meaning of concepts as well as identities are inseparable from the specific material arrangements that measure the concept or embody the identity. Therefore, conceptual understanding is not representational but rather performative. Conceptual understandings are entanglement with particular material-discursive practices of boundary making; they are embodied and practiced.

From a relational ontological standpoint, the complexity of human identities is not only due to the sheer number of variables that can influence human behavior, i.e., the epistemological problem that we cannot know everything, but also due to the constant becoming of humans (and the ongoing-ness of the world at large), or the ontological problem that being, whether human or not, is not fixed. “Being” and “knowing” are open ended, contingent, and problematic (Haraway, 1988). Boundaries and limits are temporary and shifting. Embodiment, therefore, must be treated as the effect of ongoing reconfiguration of the entangled practices of bodily production, rather than an individual action or property. Knowledge practices that treat the object of inquiry with a great deal of neglect (e.g., production of idealized models) tend to have more direct and immediate ethical implications when applied to human research. Is a beaker full of molecules much more well-behaved than a classroom full of students? Or do we get to ignore the messiness of molecule behavior with less immediate ethical consequences? Ontology, epistemology, and ethics are all inseparable from each other. If learning is possible, humans cannot be determinate beings with definite properties, but rather beings of change and becoming. And the changes that happened will have ethical consequences. The differences that researchers include and exclude have implications in what is real and knowable, and what can be ignored. The positioning of an ontological unit has ethical and epistemological implications. The philosophical implications of thinking about meaning making from a relational onto-epistemology entails that there is neither well-defined pre-existing knowledge objects for the learner to acquire, nor well-defined pre-existing learning subject to construct knowledge. Instead, from the ontology of relationships rather than objects, learning happens within cultural practices that differently enact the boundary between subjects and objects.

Agential Variation Theory

From the humanist, representationalist perspective, where knowledge is produced by the human learner representing their environment from a distance, the separation between the learner and the object of learning is absolute and the distance between them is the condition for knowledge (otherwise you will be "interfering" with the object and your representation of the object is no longer accurate). What makes the universe knowable is our ability to observe it from afar. Agential realism does not assume the absolute separation of an internal world inside the human mind and an external world "out there". Agential variation theory, on the other hand, aims to account for learning from a post-humanist/performative perspective. Knowledge and meaning do not originate strictly from the external world nor the internal human mind. Instead, the boundary that separates subject and object is enacted through the cultural practices of knowledge production, where both human and nonhuman partners contribute to each other's articulation. There is not a real world ‘out there’ and a subjective world ‘in here’. “The world as experienced is neither constructed by the individual learner, nor is it imposed upon them; it is constituted as an internal relation between them” (Marton & Booth, 1997, p. 13). Barad (2007) theorized the relation between subject and object further by giving this relation primacy and argued that we are always “already materially entangled across space and time with the diffractive apparatuses that iteratively rework the ‘objects’ that ‘we’ study”, so learning “requires differential accountability to what matters and is excluded from mattering…differential responsiveness that is accountable to marks on bodies as part of a topologically dynamic complex of performances” (p. 275).

A post-humanist, performative account of learning with external representation seeks to theorize learning without the assumptions of representationalism, metaphysical individualism, and humanism. As stated previously, the development of agential variation theory proceeded by engaging with theoretical constructs in variation theory of learning and Vygotskian sociocultural theory of learning from the philosophical standpoint of agential realism. Developed in more detail below, the central tenets in agential variation theory are: (1) the meaning of external representations is neither a property of the representations themselves nor a purely subjective construction but an enactment, and (2) learning is theorized as happening within the various intra-activities among cultural practices that (re)produce and (re)configure the learning space and the boundaries that separate and relate different subjects/objects. The proposal of this new perspective is not meant to challenge the validity of existing perspectives. Rather, this effort aims to read the different perspectives through each other to explore and push against the limits of theses perspectives from within.

As I have discussed earlier, the primary ontological unit in agential realism is phenomenon. Phenomena are ontologically primitive relations, where the boundaries and properties of the components of a phenomenon become determinate and concepts become meaningful. Since phenomena are primitive relations, or relations without relata, the various intra-actions within a phenomenon produce/constitute various subjectivities and objects of learning. Rather than taking the divide between subjectivity and object of learning as pre-existing, agential variation theory problematizes the divide between subject/object, nature/culture, knowing/being assumed in humanist representationalism. With a post-humanist, performative account, knowing is not seen as a process of a preexisting agentic subject representing a preexisting passive object (whether the object is social or natural), but an intra-action within the world's constant becoming that makes one part of the world known to another part of the world. These patterns of intra-action produce the habitus and the subjectivities that inhabits them. Agential variation theory aims to account for the various patterning and the habitus as well as the subjectivities that are associated with the patterns.

From the perspective of agential variation theory, knowledge is sedimented out of the (re)configuration of space-time-mattering where the separation of the learning subject and the object of learning is an agential one rather than a absolute one. Learning is the always already ongoing (re)configuration of the separation between the learning subject and the learning object. What makes knowledge possible is not our ability to observe from afar but the opposite: we are always already entangled with what we wish to learn, and as the separation between the learning subject and the object of learning continuously (re)configures as an effect of different practices, the subject learns and forgets. Learning is an intra-activity through which the learning object and the learning subject mutually constitute each other and emerge. Knowing does not constitute representing the world at a distance but materially engaging with the world (and differentially being in and of the world). Therefore, learning is not just about language (in the broad sense of the word), but about the mutual production of both subjectivities and the world's performative enactments. Knowing precedes the knower and the known. To exist in the world's constant becoming, we learn.

Agential variation theory does not assume a determinately bounded pre-existing learning subject and object. Rather than co-produced by learners and the learning environment interacting with each other through different activities, knowledge emerges from the intra-activities of learning that differentially make learner subjectivity and learning object bounded and intelligible to each other. The importance of intersectionality is not because of the multiplicity of labels that an individual may have, but because the entangled boundary drawing practices that put labels on bodies produce complex diffractive patterns of ethics. Students are not already-bounded individuals entering a pre-existing, fully structured learning space to engage with material that are external to them until internalization occurs. Rather, in world's becoming, ontologically heterogeneous partners, whether human or nonhuman, are brought together/apart to become who and what they are. Conceptual understanding, identity, competence, etc., these theoretical constructs enact different agential cuts. Knowing as part of the world requires being accountable for our own involvement in (re)enacting these cuts and acknowledging the contribution of maintaining normative boundaries towards perpetuating dominant values, rather than retreating to a distant and secure position of an enlightened outsider. Knowing is a relational practice with important consequences in the shaping of possible worlds. The classroom, or any learning space, is not merely a container for learners and objects of learning but specific material-discursive assemblage through which different subjects and objects become bounded and propertied.

Focusing on boundary reconfigurations is a step towards bringing together theories of identity (the production of knowing subject) and theories of conceptual understanding (the production of knowledge claims). These have usually been formulated separately while acknowledging the effect that conceptual understanding and identity have on each other. The reconfiguration of subjectivities is “becoming what the other suggests to you, accepting a proposal of subjectivity, acting in the manner in which the other address you, actualizing and verifying this proposal, in the sense of rendering it true” (Despret, 2008). The result is bringing into being semiotics that nourish materials, and materials that nourish semiotics.

Agential variation theory for chemistry education research

In biochemistry, external representations are ubiquitous in learning spaces. Similar to a blind person’s cane, external representations of biomolecules such as proteins allow us to “see” the molecules that are not visible to the naked eye. And like a white cane, the variation in intra-activities can differentially constitute external representations as either artifacts or tools. A person cannot hold a cane both firmly and loosely at the same time, and external representations cannot simultaneously be an object in itself and a representation of another object. Therefore, the referentiality of external representations is not transparently given but contingent on the intra-activities of which it is a part. Student understanding of external representations is not a result of discerning the various aspects of an object from afar, but emerges from differentially engaging with the materiality of external representations. Agential variation theory reconceptualize the role of representation in biochemistry as an intra-active practice embedded and embodied in a network of sociotechnical practices.

Student experiences with representational practices are not stored like data in a hard drive, they are storied and narrated. Lived experiences are the storied effects of the material-discursive re(con)figurations in the world's ongoing becoming. The teaching and learning of science are historical events entangled with the rest of the world where patterns of story emerge through the intra-action that agentially separate one part of the world from another part of the world, where different beings (science, student, instructor, curricular, pedagogy, classroom space, education technology, representations, etc.) are differently oriented and made intelligible in their mutual constitution. These patterns of stories and the bounded parts of the world are in a reflexive relationship. Rather than thinking about representations as passive material objects with specifications, they are a slice of the tentacular practice of science teaching and learning with their own agency. Studying representations can trace the patten of entanglement that involve different technoscientific practices. The materiality of the representations is historicized: paper, printing, digital mediums, are all historic artifacts of representational practice. They become bounded parts in iterative mutual constitution with the patterns of stories around them.

As such, agential realism is a realist onto-epistemological framework for integrating the material, the discursive, and semiotics within educational research and offers a number of contributions to mainstream chemistry education research on external representations, the most salient of which are: clarifying the irreducible tripartite relational nature of meaning (i.e., the meaning of signs involves a signifier, a signified, and a boundary between them enacted by signifying practices that separate and relate the signifier and the signified), extricating the concerns of representation in chemistry teaching and learning from representationalism, and promoting increased methodological sophistication by moving beyond quantitative assessments of student representational competency.

As I have discussed earlier, a crucial aim of engaging with feminist new materialism in education research is to undertake research where the mutual entailment of discourse and matter is explored. When matter was privileged over discourse, variations in the materiality of representations such as color, size, or position, were the focus of analysis, while the discourse of making sense of representations was viewed as a fairly transparent process of discernment. On the other hand, when discourse is privileged over the material, the focus of research is on how knowledge is discursively constructed while the materiality of learning environments is viewed as being shaped by discourse and serve discursive purposes. Agential variation theory attempts to avoid getting stuck in this power-producing binary by understanding the discourse/material of learning as a mixed and entangled cultural-natural phenomenon. This perspective is especially useful for science education research as scientific concepts are not ideational only but have their epistemic sources from material engagements in the world. They are not only semiotic tools for thinking about the world, but also material instruments for engaging and transforming the world. As Barad pointed out: "Neither discursive practices nor material phenomena are ontologically or epistemologically prior. Neither can be explained in terms of the other. Neither is reducible to the other. Neither has privileged status in determining the other. Neither is articulated or articulable in the absence of the other; matter and meaning are mutually articulated" (Barad, 2007, p152). Seeing matter and meaning as mutually articulated shifts how learning with representation is theorized. The meaning of representations is neither an intrinsic property of the material of the representations nor is it an abstract ideation untethered from the material. Rather, the material of representations is an active participant in the articulation of their meaning.

Guiding research questions

The chapters thus far described a theoretical movement towards a post-humanist performative perspective on learning through engaging with multiple theorists and working within/against different disciplines. In the following chapters, I will describe a similar movement in the methodological and analytical space to push qualitative research in chemistry education towards a trans-disciplinary mode of inquiry. The methodological consideration will be contextualized in transcript data from semi-structured interviews with undergraduate biochemistry students about G proteins with external representations. Three research questions are produced from the general orientation of the various philosophical and theoretical considerations in agential variation theory. In turn, these research questions guide the theoretical, methodological, and analytical experimentations that move the researcher subjectivity through the research space and the theoretical constructs enables different analytical interactions between theory and data to move analysis forward. The three guiding questions are:

1. What are the different material-discursive-semiotic bricolages that emerged from thinking with external representations in chemistry to enact the meaning of GAP/G protein function?
2. How does the meaning of undergraduate biochemistry students' linguistic expressions emerge within the bricolage of representational practices that produce the meaning of GAP/G protein function?
3. How does the materiality of external representations intra-act within the reconfiguration of the material-discursive-semiotic bricolages that enact the meaning of GAP/G protein function?

Chapter 4: Methodological Considerations

In previous chapters, I described an exploration into the theoretical implications for critically reflecting on the normative philosophical assumptions and engaging with insights from agential realism. To put these theoretical implications into practice, it is necessary to engage in methodological experimentation with transdisciplinary methodologies developed in fields such as cultural and science studies, as scholars in these fields are similarly conducting research that attends to the entanglement of the natural sciences and society. In the tradition of qualitative research, Brinkmann (2015, p. 620) argued that the normative ways of doing qualitative research, which he referred to as "good old fashioned qualitative inquiry" (GOFQI), privilege humanist interpretive methodologies which work under the assumption of representationalism, metaphysical individualism, and humanism. One of the broadly shared purposes of engaging with feminist new materialism such as agential realism is to contest GOFQI. Feminist critique of science has argued that science attempted to play the "god trick": seeing everything from nowhere (Haraway, 1988). The "light" of the researcher subjectivity shines into the formless darkness that is "nature" and produces a representation of an independent nature. In the context of education research, the researcher's role is to "capture and understand [students'] perspectives, usually via dialogue (often framed as qualitative research interviews), and try to give them voice (especially those whose voices are rarely heard)" (Brinkmann, 2015, p620). In recent years, science education scholars voiced their concerns about GOFQI and engaged with feminist new materialism to posit different onto-epistemological standpoint for science education research (Bazzul, Tolbert, & Kayumova, 2019). Recognizing the limits of GOFQI does not mean rejecting it completely; instead, the goal is to work within and push against the limits. In this chapter, I will first discuss the methodological experimentation prompted by engagements with feminist critique of science. Then, I will describe the study context to provide background information on the transcript data used in analysis before delving into the findings.

Onto-episte-methodological (un)framing

> Thought does not need a method…Method in general is a means by which we avoid going to a particular place, or by which we maintain the option of escaping from it.
>
> – Deleuze, 1983, p. 110

Under the normative worldview prevalent in discipline-based education research, data is conceived as a still object to be manipulated and processed based on the researchers' preferences or predetermined procedures. The meaning of data is often seen as fixed and waiting for discovery/representation. Research practices operationalizing such ontology and epistemology aim to produce "meaningful data chunks", that is, themes and categories with clearly defined boundary conditions and validated through interrater reliability testing. From the position of an enlightened outsider, the researcher is tasked to discover the true meaning of data and to create an authentic and accurate representation of qualitative data. Extraction, coding, and sorting forms the normative mode of analysis that creates ordered data objects as findings. Haraway (1988) discussed such a view of knowledge production as the "god trick" of Western Modern Science, which is the idea that by being everywhere and nowhere at the same time, that is, being further away, higher up, and in charge of a global view, we can see reality, facts, truth, and knowledge more clearly and objectively. Haraway (1988) criticized this masculinist, scientistic, colonialist view of objectivity and called for a feminist epistemology which centers situated and embodied knowledge where "the closer in we travel, the more likely we are to see". Traveling closer in a movement that Barad (2007) called "meeting the universe halfway", agential realism puts forward a relational onto-epistemology where the researcher subjectivity occupies a position that is agentially separated within a phenomenon rather than the position of an enlightened outsider absolutely separated from the phenomenon being researched.

If we take agential realism as the onto-epistemological foundation for research, subjects and objects would not preexist their entanglement, rather, ontologically heterogeneous partners become who and what they are in relational material-semiotic becoming (Barad, 2007). Recognizing matter as equal partner in knowledge production means rethinking the relationship between theory and data, giving data its due of agency. The optical metaphors for research can help illustrate this rethinking. Both reflection and refraction have been used as optical metaphors for research. Reflection illustrates a view that theory is a mirror image of data and reflecting it, while refraction illustrates a view that theory is a lens through which to view data. When thinking from a relational ontological standpoint, the metaphors of reflection and refraction are no longer appropriate for the relationship between theory and data. Theory is not a reflection of data (reflection), nor is it a lens through which data is viewed (refraction). Rather, both theory and data make up the material-semiotic apparatus of knowledge production. Ontological cuts are enacted to separate the world into entities through material-discursive boundary drawing practices. Therefore, the goal of research is not producing a representation of an external reality but to trace one's entanglement within a phenomenon. In this study, analysis traces the patterns of biochemistry representational practices diffracted through theory and data. In biochemistry education, representational practices are entangled with a variety of technological, scientific, social, pedagogical, and ethical practices in the sense that they do not pre-exist but mutually constitute each other in the iterative materialization of biochemistry learning spaces. Representational practices cannot be separated from the other practices and be investigated in isolation.

The researcher's position, therefore, is that of a lost subject who is entangled in the effects of relational material-semiotic worlding (data) to trace the patterns of nature-culture relationships and assemblages (phenomenon). As such, rather than a position of nowhere or a fixed positionality, the researcher's position is "always a complex, contradictory, structuring, and structured body" (Haraway, 1988). Such a conception of data and researcher subjectivity prompts researchers to be attentive towards "data wants" and resist the temptation, particularly when overwhelmed by the quantity of data and volume of data material, to ask brief, uncritical questions about data that result in data interactions and findings that resemble lists of materials and examples of collected quotes (Koro-Ljungberg, 2015).

As discussed in Chapter 2, a significant portion of knowledge production efforts in DBER is framed methodologically (Bussey, Lo, & Rasmussen, 2020), demonstrating the productive power enacted through methodological language and labels. The use of methodological language and labels in qualitative research contributes to the enactment of a particular onto-epistemological space. Methodological language and labels are developed within a particular historical and cultural context, reflecting power, legitimacy, and historical markers (Koro-Ljungberg, 2015). Foucault (1995) argued that knowledge and power are inseparable, and that "there is no power relations without the correlative constitution of a field of knowledge, nor any knowledge that does not presuppose and constitute at the same time power relations" (p. 27). Therefore, it is important to articulate new methodological language and labels along with theoretical constructs. In the following section, I will introduce Haraway's notion of String Figure, or SF as a metaphor to articulate a different approach to qualitative inquiry in more detail. Theories are not compared and contrasted with each other but rather weaved into each other along with data. Instead of serving as lenses, theoretical frameworks enact analytical boundaries that both enable and constrain thought. Through SF, the enacted boundaries in the analytical space are reconfigured where some thoughts become (un)thinkable, that is, (un)available to think with.

String Figure (SF) as a metaphor for qualitative data analysis

The method of data analysis of this study draws on the transdisciplinary methodology put forth by Donna Haraway, namely string figures, or SF (Haraway, 2016). Transdisciplinary methodologies aim to produce ways to work in a fluid methodological space beyond the boundaries of any single discipline. Emphasizing on the instability of boundaries and insisting that objects of knowledge are agents in the production of knowledge, Haraway had put forth the notions of cyborgs (1985) and material-semiotic actors (1988) in her previous work, which both served to unsettle the normative boundaries of humanity and humanity's exclusive access to agency. Similarly, instead of providing a bounded definition to the concept of string figure, Haraway (2016) dissolved the concept in a "ubiquitous figure" indicated by the initials SF, which can stand for "string figures, speculative fabulation, speculative feminism, science fact, and science fiction". For Haraway (2016), SF takes on the role of a methodological lodestar by which material-semiotic actors (e.g., theory, concept, data, researcher subjectivity, etc.) can be constellated in transdisciplinary storytelling. Differentiating is about agential separability rather than absolute exteriority. Differences are not treated with a practice of othering but a practice of making connection. The intra-actively emergent "parts" of phenomena are mutually constituted and always already entangled.

In her Pilgrim Award acceptance speech, Haraway (2013) characterized SF as "a game of cat's cradle or string figures, of giving and receiving patterns… of relaying connections that matter, of telling stories in hand upon hand… to craft conditions for flourishing in terran worlding". For biochemistry teaching and learning, particularly in the context of learning with external representations, SF can be a useful approach for understanding learning as a process of giving and receiving patterns to craft conditions for external representations to become meaningful. The same can be said for research: theory and data are relaying connections that matter; researcher subjectivities and research subjects continuously give and receive patterns, telling stories hand upon hand. SF methodology place the focus of research on relations rather than objects and attends to the changing patterns of relations rather than the change in properties of objects. Shown in Figure 3.1, with ecology as the topic of interest, Haraway's illustration of SF includes both human and nonhuman as partners in the practice of collaborative survival (Haraway, 2016). In the context of this study, SF helps with tracing how student conceptions and meaning of representations become different when entangled as partners in representational practices.

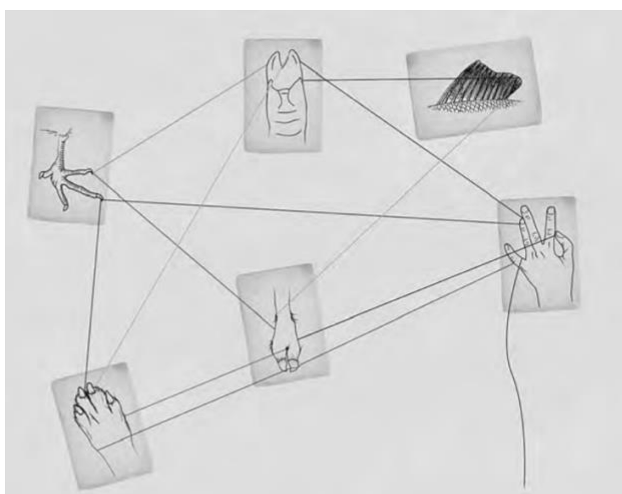

Figure 4.1: SF can be played by many, both human and nonhuman. SF is about the rhythms of giving and receiving patterns (Haraway, 2016).

All materiality is socially, historically, culturally, and politically constructed, and likewise, the social, historical, cultural, and political realities are physically constructed. Barad (2007, p.55) pointed out that "to theorize is not to leave the material world behind and enter the domain of pure ideas where the lofty space of the mind makes objective reflection possible; theorizing, like experimenting, is a material practice". SF takes up the notion of theorizing as a material practice and replaces vision with touch as a metaphor for research. SF is about forging partial connections through situated knowledge and local specificities. Just as hands and string take mutual shape in a game of cat's cradle, theory and data mutually constitute each other in SF analysis. During the course of analysis, researchers will be encountering difficulties, dropping loops, picking them back up, making and unmaking patterns, and often improvising. This is what SF enables: unexpected combinations of theory-data as string figures folded and enfolded, connived, and collapsed into each other (Taylor, Tobias-Green, Sexton, & Healey, 2022).

SF can be thought of as a triple sense of figuring. First, SF is tracing the tentacular practice of knowing, where different subjectivities, positionalities, and identities become bounded and articulated to each other. Second, SF is the different patterns of material-discursive assembly, i.e., learning spaces, that solicit response. Third, SF is becoming with data in surprising relays, recognizing how data (object) can make a discovery of the researcher (subject) during data analysis. SF is a methodology for tracing the patterns of the world's stories by tracing the researcher's own entanglement that acknowledges a collection of knowledge makers. SF can be used to illustrate the vast and often unpredictable possibilities for material-semiotic engagements across multiple contexts when humans and nonhuman companions constitute new ways of collaborative knowledge production. Through SF, the researcher subjectivity, the participants, and other material-semiotic artifacts of research, are constituted reflexively.

String figure research refuses pre-existing methodological handholds in favor of responding to the forces that bubble up around the researcher. Unlike GOFQI that dictates a certain type of analytical interaction with data and expects a certain form of output before any analysis was done, String Figuring creates a space in which research could be done, but what might actually be done in terms of methods or outputs was not known or tied down in advance. However, String Figuring is also not groping blindly in an ill-defined research space. The analysis is situated within, and aligned with, the aim of the project: to investigate how "new" educational spaces are produced and made inhabitable by various natural-cultural, material-semiotic practices. We invite SF into our research space not in the way of "we will plan and do analysis like this" but in the way of "what happens if?". In this sense, string is a participant which might allow researchers to see things differently. The happenings-doings-thinkings are "beyond inherited categories and capacities, in homely and concrete ways" (Haraway, 2016, p.7).

In recent years, scholars in science education began experimenting with SF as an approach for conducting qualitative research. Tolbert and Bazzul (2020) engaged with SF for a radical aesthetic shift in science education. Drawing on the shift of art from the Regime of Representation to the Aesthetic Regime of Art where a break with art-as-representation disrupted the normative relationship between art, aesthetics, and daily life, Tolbert and Bazzul argue that science educators' efforts to pursue science for justice involve disrupting the aesthetics of what science classrooms look like and feel like. Sociopolitical engagement in science education must be accompanied by significant shifts in the everyday aesthetics of science teaching and learning. Turning towards SF for a radical aesthetic shift is recognizing that the political and democratic potential for science teaching and learning is not just a question of ideology and discourse, but also a question of what is sensible or possible to see, do, feel, and sense. There is always a particular aesthetic, a way of orienting, to science and science education such that certain material-semiotic practices are rendered normative and commonsensical. Therefore, tracing and shifting what is sensible and visible is foundational for work that aim at sociopolitical engagement in science education.

SF and writing as inquiry

Using SF as a methodological lodestar instead of relying on structures of methodological labels, I am attempting to engage in what Koro-Ljunberg (2016) termed "methodologies without methodology" and embrace the multiplicities and uncertainty embedded in different theoretical and methodological configurations. The goal is to think with theory and effectively open up the process of data analysis in qualitative research (Jackson & Mazzei, 2011). Using a common data set and coordinating various theoretical perspectives, this approach pushes against traditional qualitative data analysis such as mechanistic coding, reducing data to themes, and writing up transparent narratives. By refusing a closed system for fixed meaning, this analytical approach aims for a dense and multi-layered treatment of data that pushes research and theory and data to its exhaustion in order to produce knowledge differently. In addition, the multiple lines of data analysis parallel the theoretical development detailed in previous chapters. This analysis is both a movement from classical ontology and epistemology (i.e., representationalism, metaphysical individualism, humanism) to posthumanist performative onto-epistemology, and a trace of this movement that serves as an articulation of the methodological experimentation. In this sense, writing is not to represent products of inquiry but to engage in the process of inquiry.

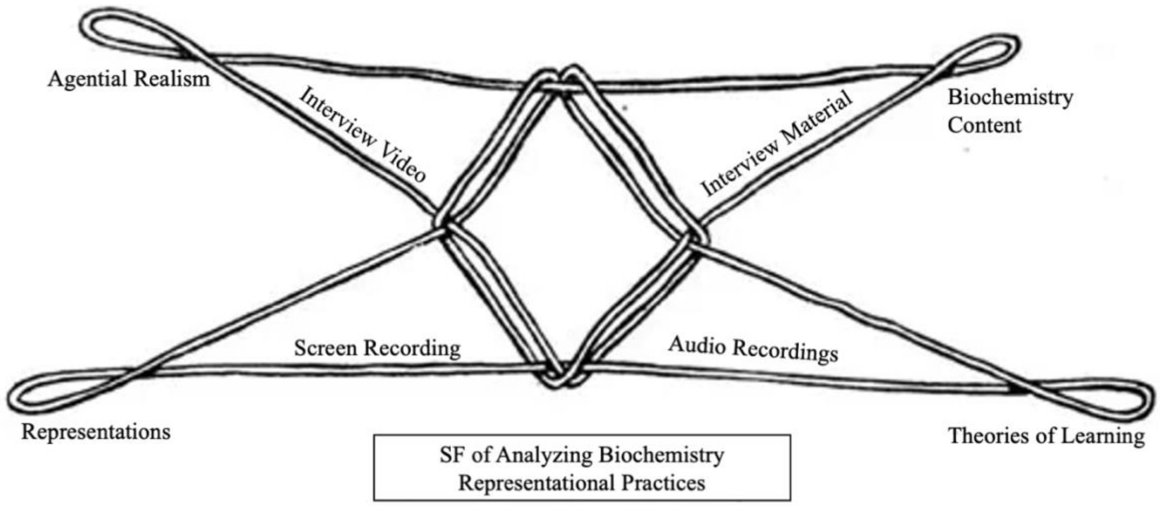

Figure 4.2: An illustration of SF methodology in the context of this dissertation.

As shown in Figure 4.2 above, theorization and data analysis are treated as entangled processes. Rather than applying theory as a finished product to data (as demonstrated with the refraction metaphor where theory is a lens through which data is viewed), theoretical development and data analysis are viewed as entangled practices of knowledge production. Working within and against the truths of humanist, conventional, and interpretive forms of inquiry that dominated qualitative research practice, the multiple beginnings and multiple movements through the analytical space continuously reconfigures both theory and data to produce dense and multi-layered meaning from theory-data. Instead of one set of research questions informed by one particular theory, SF weaves together multiple theory-data assemblages.

SF and research reflexivity

> There is no difference between what a book talks about and how it is made.
> --- Deleuze and Guattari, 1987, p4

Reflexivity has become an important topic of discussion among qualitative researchers in educational studies. Reflexivity is generally described as a deconstructive exercise for critically examining the intersections of author, text, and world (Macbeth, 2001). Contemporary expressions of reflexivity problematize meaning, value, knowledge, and representation (e.g., Bourdieu & Wacquant, 1992). With roots in critical self-reflection, reflexivity is conceptualized as "the turning back of an inquiry or a theory or a text onto its own formative possibilities" in order to relieve the gendered, cultural, rational, and other hegemonies to attend the competing knowledge claims in the worlds researchers investigate (Macbeth, 2001). The goal of reflexivity in qualitative research is not to merely acknowledge one's own biases or to criticize naïve realism, but to produce reflexive analytic texts for the field. The task is to confound what we know and thereby construct what we do not understand.

Reflexivity begins with a skepticism towards how we have been speaking, describing, reading, writing, and representing. Macbeth (2001) discussed three types of research reflexivity: positional reflexivity, textual reflexivity, and constitutive reflexivity. Positional reflexivity concerns the examination of standpoint, biography, self, and other to understand their influence on analytical interactions with data. The reflexive exercise is a self-referential analytic exercise that takes up the positioning of the researcher with a vigilance for privileged relationships between researcher and the world. A positionally reflexive view of research thus implicates an articulation of the researcher's analytically situated self, often with autobiographical attachments. In educational studies, positional reflexivity has been recommended as an essential component of qualitative methodology, forming a basis for postpositivist and post-structural analytic rigor (Ball, 1990; Hertz, 1996; Lather, 1994). Ball (1990) argued that the possibility of technical rigor in qualitative methodology has its basis in the "conscious and deliberate linking of the social process of engagement in the field with the technical processes" and called such linking reflexivity. Positional reflexivity thus aligns methodological rigor with a critically reflective research subjectivity.

Starting with a skepticism towards the binary of sign and referent, textual reflexivity concerns the examination and disruption of the practice of textual representation. Although positionally reflexive analyses need not be textually reflexive, textual reflexivity requires positional reflexivity since authors are unavoidably implicated in the practice of textual representation. The goal of textual reflexivity is to resist the expectations of a text that is available to realist readings (Macbeth, 2001). Textually reflexive writing aims to write the disruption of the realist assurance about the transparent referentiality in representations into the produced text through the disruption of the text itself by experiments in textual display (Macbeth, 2001). Textual reflexivity focuses on uncovering the "unthought categories of thought which delimit the thinkable and predetermine the thought" (Bourdieu & Wacquant, 1992).

Rather than a reflexivity of critical self-reflection or textual deconstruction, constitutive reflexivity is concerned with how it is that our accounts of the world reflexively constitute what they account for. From this perspective of reflexivity, formulations of "what happened" is a constitutive feature of what happened. Constitutive reflexivity aims not only to disrupt the normative practice of textual representation, but also to rethink the relationship between the text and what the text is about. Judith Butler wrote, "In speaking of the 'I', I undergo something of what cannot be captured or assimilated by the 'I', since I always arrive too late to myself" (Butler, 2005, p79). If the "I" of the researcher as well as that of the participants are always in a state of becoming, it raises the question of why a particular model of linguistic representation, one where signs stand for objects or meanings (e.g., "I" as a sign that stand for researcher subjectivity as an object), should provide the framework for reflexivity (Lynch, 2000). From a constitutive perspective, descriptions of thoughts are constitutive parts of thoughts rather than external representations of thoughts. Correspondence between language and reality is rendered irrelevant in constitutive reflexivity.

SF aims to preserve and recover the polysemy of multiple positions, interests, and agencies in the settings it analyzes rather than representing the world with a singular, objectivizing narrative voice. The aim is to enact a process of research that is simultaneously using, producing, and questioning the practices that are and have been available to us. Going beyond the idea that reflexivity and analysis as inner mental activities in the mind of the researcher understood as separated from the data, SF attempts to "meet data halfway" and make visible new kinds of material-discursive realities that can have transformative consequences.

Study Context

The context of this study is a project aimed at advancing biomolecule visualization tools for college courses. Utilizing augmented reality technology, the project team developed an application, BioChemAR, that use the camera on modern smartphones and tablets to superimpose protein models onto a QR code (Sung, et al., 2019). A total of three protein models are available through the BioChemAR application: hemoglobin, potassium channel, and G-protein. The application is preloaded on iPads, which were provided to students during course instruction on topics pertaining to the available models.

The overarching project collected a large amount of interview data on students using the AR model to answer a series of questions regarding the structure and function of the represented protein. A total of 24 interviews about the different models of AR were conducted. The data analysis presented here will focus on a subset of 4 interviews. The rationale for selecting the subset of interviews is twofold: 1) this subset of interviews utilize a version of the AR model that involves a QR cube rather than a flat QR code to facilitate haptic interactions, 2) the interview protocol for these four students involved the participants proposing and revising a model for G protein's catalysis of GTP hydrolysis with various forms of external representations made available in sequence, this structure is well suited for SF analysis as the interview produces multiple stories about G protein as the materiality of representations of G protein reconfigures.

Each interview started with general questions about the interviewee's recent life. The interviewer brings in the interview material, and with the interviewer's opening remarks, we begin to see an assemblage of material and discursive practices becoming "the interview", a familiar interactional organization for educational researchers. The normal order of the room that these practices achieve routinely shows a two-party organization of speaking and listening. The two parties are the interviewer and the interviewee as a cohort, and the order of the interview space is constitutionally reflexive of these situated identities. The interviewer and the interviewee reflexively assemble the structure of the interview space as they jointly produce and implicate each other in their understanding of the social context.

The analysis works from transcripts, which are intentional texts developed from prior work on investigating how students use the AR technology. As an analyzable text, a transcript is developed to shape the possibility of its own writing, reading, and analysis. Transcripts attempt to record the temporal, interactional production of the interview, and account for how things were said and done in concert over the course of the interview. In this relational account, what is made available to the researcher in transcripts is a record of the practical production of an interview coming to order, meaning, and structure through situated actions.

Data sources

The data in this dissertation is produced through a traditional methodological research practice, i.e., interviewing. Interviewing is traditionally based on the assumption that "voice makes present the truth and reflects the meaning of an experience" (Mazzei & Jackson, 2009). In the context of this study, the voice of the interviewee makes present the truth about their conceptions about G protein and reflects the meaning of a learning experience with various external representations. Analysis of interview data is therefore understood as interpretation of what the interviewee really means, a mental process of naming, structuring, and representing. Underpinned by representationalism, this interpretive mode of data analysis positions the interviewee as the source of meaning that enables the researcher to construct themes that leads to the production of a coherent, interesting narrative about student learning. Jackson and Mazzei (2012) instead suggest that interview data can be used to push against the limitations of interpretation: to understand interview data as partial and incomplete, where one narrative is always being told in place of another possible narrative. While the research project that informs this dissertation is a traditional cognitive interview study in many ways, the engagement with agential realism and SF moves the analysis beyond the representational mode of trying to figure out what the interview participants "mean" and describing transparent narratives with themes and patterns. I will be using de-identified transcripts generated from video and audio recordings of student interview as the primary data source for analyzing biochemistry representational practices. A total of four interviews involving external representations related to G protein are included in the study.

The structure of student interviews resembles traditional cognitive interview with a focus on using external representations in biochemistry. Students were asked to work through two tasks about the structure and function of G proteins and GAPs. In Task A, students were first provided with the reaction equation of GTP hydrolysis and asked to propose a model for how GAPs would facilitate GTPase activity, specifically, how GTPase carry out the hydrolysis of GTP with the help of GAPs. Then, students were provided with cartoon diagrams of two GAP-GTPase complexes (Ras/RasGAP and Rab/RabGAP) and asked to revise their previously proposed model. In Task B, students were first provided with a cartoon diagram of the active site of heterotrimeric G proteins and asked to propose a model of how heterotrimeric G proteins would rely on GAPs to carry out the hydrolysis of GTP. Then, students were provided with AR models of heterotrimeric G proteins (one without binding GAP and one bounded to GAP) and asked to revise their previously proposed model of heterotrimeric G protein function.

Study participants

Participants of this study were undergraduate students enrolled in a Fall 2021 biochemistry course at a private college in the Midwest. A total of 40 students were enrolled in the course. A total of four students (pseudonyms: Mary, Jessica, Bobby, and Nicholas) participated individually in the interview study. Interview participants were each compensated with a $10 Amazon gift card. During the interview, participants were asked about their experience with the biochemistry course, prior experiences with AR technology, and their general opinion of AR. Participant responses to these questions informed the descriptions of the participants. In the following section, I will provide a brief description of each interview participant.

<u>Mary</u>

When asked about her experience in the biochemistry course, Mary mentioned that she thought it was "pretty difficult in some ways" where she thought she understood the content well but "didn't always do great in answering questions". She found the homework prompts were often more difficult than what she first perceived them to be. In terms of previous experiences with AR, Mary had limited experience with AR-based mobile games, but also mentioned that she had some brief experience with the Oculus virtual reality system. Mary's opinion of AR is also influenced by the portrait of AR in popular culture such as medical TV programs where AR was shown to illustrate human anatomy.

Jessica

Jessica took a year off from school due to the pandemic. She took biochemistry after coming back to prepare for the MCAT exam and work towards her goal of attending medical school. She found the course to be overall enjoyable and rewarding. Particularly, Jessica enjoyed learning about the interactions between amino acids and the implications that these interactions have on biological processes. However, she found reading primary literature challenging because of her unfamiliarity with the jargon used in those readings. Jessica also mentioned that she did not have any prior experience with AR.

Bobby

Bobby also enjoyed the biochemistry course. He enjoyed organic chemistry and found learning about the structure of proteins and the chemistry behind protein function engaging. He also found that the biochemistry course is challenging due to the large amount of information. Previously, Bobby had experiences with AR in mobile game settings and had some experiences with VR.

Nicholas

Nicholas enjoyed the biochemistry course for its connection between biology and chemistry, two subjects in which he has always had an interest. He particularly enjoyed learning about the chemical basis behind the biological processes to develop a more nuanced understanding of ideas he had simply accepted. Nicholas found the problem sets especially challenging because he felt that although the concepts covered in the course were not difficult for him to understand, his understanding of these concepts covered was often insufficient for completing the problem sets. Previously, Nicholas had experiences with AR in video game settings. He found AR to be interesting particularly for its potential to go beyond creating videos. Compared to VR, Nicholas found AR to be more accessible as less hardware is required for utilizing AR.

Integration of Agential Variation Theory and SF

This study thinks with SF in the interstices of theory, methodology, representation, and learning with external representations in biochemistry. It is a theoretical and methodological experiment in producing situated knowledge in chemistry education research (Haraway, 1988). As a conceptual exploration, I created relations and connections between ways of thinking with theoretical constructs rather than compared and contrasted them. Figure 4.3 below illustrates the theoretical constructs that were thought with data to weave patterns of meaning with data and theory. These theoretical constructs both situated the data analysis and were situated within the data analysis. The construct of chemistry cultural practices emerged from thinking about external representations in chemistry from a relational ontology: rather than viewing external representations as tools that can be used at different competency levels, I viewed external representations as phenomena whose meaning emerged within chemistry cultural practices that relate together semiotic features, signifying practices, and the participation of materiality. Thinking with these three theoretical constructs can give voice to different participants in the enactment of meaning. Tracing semiotic features gave voice to the interviewee as participant in the enactment of meaning by articulating the chemistry concepts expressed by the interviewee when thinking with external representations. Tracing signifying practices gave voice to the context of the verbal expression as participant in the enactment of meaning by articulating the orientation of the chemistry concepts expressed by the interviewee. Tracing the participation of external representations' materiality gave voice to materiality as participant in the enactment of meaning by articulating its role in providing materiality to semiotic features.

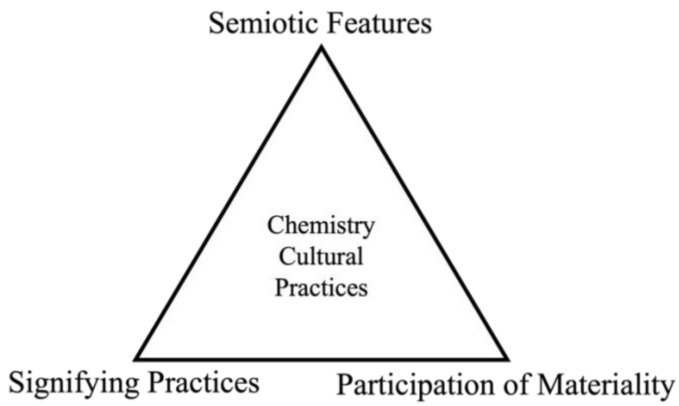

Figure 4.3: Theoretical constructs for thinking with data.

Thinking with boundary reconfiguration and weaving patterns of meaning with data and theory, the analysis started with identifying semiotic features of the external representations. This process treated the external representation as the object (holding the cane loosely to feel the features of the cane). Then, the analysis reconfigured to highlight how the semiotic features of external representations were related together by signifying practices. This process viewed the external representation as part of the subject (holding the cane firmly to sense surroundings). The analysis reconfigures again to introduce the construct of material intra-action that places external representations as partners with interview participants. As the materiality of the external representations changed, the meaning of G protein function was differently enacted within the intra-action. The participation from materiality of the external representations was highlighted as an important aspect of the enactment of meaning. AR affords a materiality that is unique in the sense of the possible interactions with the external representation. It has a material component other than the electronic device, i.e., the cube with QR codes but it also has features of a virtual model.

The coordination of the added material component with the virtual model aims to both add a physical aspect to the virtual model as well as augment the physical object with the virtual model. AR models represent a mode of external representation that sits at the boundary between virtual and real. The mutual constitution between the virtual and the material produce the AR object. The mutual constitution between the students' subjectivity (someone who holds a certain conception) and the meaning of the external representation is also entangled with the relationship between the virtual and the material.

The task structure of the interview presented a unique site for the theoretical and methodological experimentation. With agential realism's notion of material agency, external representations are thought of as active participants in the construction of their meaning rather than having an inscribed meaning waiting for interpretation. Although these different external representations can be considered as referring to the "same" process, i.e., the hydrolysis of GTP by GAP-GTPase complex, they could make the process visible in different ways and enact different meanings within the relationships that produced the interview space. In this context, I thought with SF in two ways: the ongoing reconfiguration of the relationships that differently produce learner subjectivity and meaning of external representation, and the ongoing reconfiguration of the relationships that differently produce researcher subjectivity and meaning of interview data. The relationships between learner subjectivity and meaning of external representation were illustrated though the construction of various string figures of student conception.

As I have discussed earlier, the goal of this project is not about creating accurate portraits of the participants lives and thoughts. The inclusion of participant descriptions may seem like an attempt to start with transparent narratives that represent interview participants, which would contradict the goal of this project. However, including some backstories for all participants can provide important contexts and insights for situating the analysis that focused on their interactions with external representations in semi-structured interviews. I caution that these backstories are limited and do not provide fullness to the data, but they can provide insights to readers on the backstories in my mind as I thought with theory and data.

The theoretical, methodological, and analytical developments detailed so far is a process of moving from taken-for-granted normative ways of thinking by ways of new philosophical encounters and engagements. One important aim of this dissertation is to explore the possibilities of reading text from different academic traditions diffractively into each other, weaving different disciplinary insights into each other with the help of SF to produce new patterns of meaning. Instead of asking the interpretive question "what does it mean?" when reading theory or analyzing data, the researcher shift towards asking "how does theory or data work?" and "what does theory or data produce?" In this sense, writing is an embodied and material act of inquiry, rather than an abstract process of linguistic representation.

In chapters 5, 6, 7, and 8, I will discuss the SFs that were generated from thinking with data and agential variation theory. Although the findings are unavoidably presented in order, this order of the text is not intended as a continuum. Rather, the findings can be thought of as string figures in a game of Cat's Cradle. In this sense, each interview is treated as an event where the meaning of G protein was differently enacted. The SFs presented in the following chapters constitute as a trace of the reconfiguration of patterns of meaning. The findings of the analysis will be presented as researcher's narrative that emerged from thinking with the different theoretical constructs and interview segments. The experimentation with researcher's reflexivity was embodied in the narrative by giving voice to the different aspects of chemistry cultural practices that participated in the enactment of the meaning of G protein function. The meaning of data was differently enacted within the intra-actions between researcher, theoretical constructs, and data that reconfigured the narratives that were told in the analysis to produce more nuanced readings of theory and data. After presenting narratives from thinking about the interview data with different theoretical constructs, I will present an overall SF for each interview event. The SFs may resemble concept maps, but there are important theoretical distinctions that must be considered when interpreting the two different types of figures. The use of concept maps is often associated with research on the associative structure of student conceptions from a cognitive perspective. The concept maps are seen as a representation of the knowledge structure of the learner. SF, however, cannot be attributed solely to the learner. SFs are maps of meaning weaved together by the assemblage of human and nonhuman that constitute the research space to temporarily hold meaning still. They can be thought of as tracing the researcher's intra-activity within the research space created by the assemblage of theory and data.

Chapter 5: SF from Tracing Bobby's Interview Event

In this chapter, I will trace the material-discursive-semiotic assemblage that emerged during an event where different external representations of G protein were made available for Bobby to think with while answering a series of interview questions. The analysis will be presented in four sections. In the first section, I will trace the assemblage that emerged when a reaction equation was made available for Bobby to think with. In the second section, I will trace the assemblage that emerged when a cartoon diagram of G protein was made available for Bobby to think with. In the third section, I will trace the assemblage that emerged when an AR model of G protein was made available for Bobby to think with. And lastly, I will present an overall SF for the interview event with Bobby. As I discussed earlier in chapter 1, the texts presented in this chapter are not meant to serve as an attempt to create a transparent, singular narrative about what "really" happened during the interview event with Bobby or what Bobby "really" had as his mental image. Instead, the texts presented in the findings are tracings of thoughts that were made possible to think with when engaging with the post-humanist performative perspective discussed in agential variation theory. The meaning of the findings emerged within the intra-action between the philosophical, theoretical, and methodological considerations and the text in this chapter.

Thinking with Reaction Equation

The external representation that was available for Bobby to think with is shown below in Figure 5.1. The reaction equation was depicted with the structural formulae of the educts, transition state, and products. Segment 5.1 below shows the interview transcript excerpt.

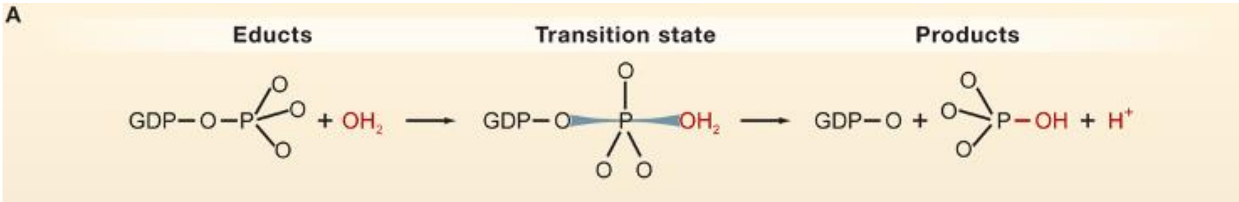

Figure 5.1: Reaction equation of GTP hydrolysis.

Segment 5.1

> Interviewer: With this reaction equation, could you propose a mechanism for G protein function?
> Bobby: Yeah, so just had a SN2 attack originally with the OH_2 group, the phosphate, and then the proton here gets kicked or kicks its electrons onto the oxygen, onto the phosphorus, and then kicks off the GDP group. And then, the new... and that was the transition state and then you have your product.
> Interviewer: What do you think the role of the G protein is?
> Bobby: I actually have no idea. Um… just stabilizes the original reactant possibly or is an energy source for the product.
> Interviewer: Could you say a little more on this stabilization?
> Bobby: Yeah, I just think that because the substrate is there originally, but then the water comes in, which is more favorably stabilized I suppose. So maybe this is trying to isolate the G protein through this process. But I don't really know, at all.
> Interviewer: What do you mean by isolate?
> Bobby: To get kicked off alone, because it's attached to the phosphorus group, and then after this process it's just attached to an oxygen. Uh, I don't know anything about G protein, so I just need to know more about that.

Tracing semiotic features

Thinking with semiotic features and the interview segment above, I saw that when proposing a model for G protein function with the reaction equation, Bobby started with proposing an arrow pushing mechanism for the hydrolysis of GTP. Bobby proposed an SN2 attack where "the proton kicks its electron onto the oxygen, onto the phosphorus, and then kicks off the GDP group", and the products would form afterwards. When the interviewer asked Bobby about the role of G protein, Bobby first expressed that he did not know, then speculated that G protein could stabilize the reactants or act as an "energy source for the product". When further elaborating on the meaning of stabilization, Bobby speculated that G protein was isolated in the process of stabilizing the substrate. However, he qualified both of his statement by mentioning that he did not really know, going as far as saying that he did not "know anything about G protein".

Thinking with semiotic features, I understood the meaning of G protein function as enacted through the features articulated by Bobby: SN2 attack, GTP structure, movement, transition state, stabilization, and energy. The intra-activities among these features enacted a meaning of G protein function that primarily articulated the changes of the substrate. For example, the meaning of SN2 attack was produced through the intra-activities that also articulated GTP structure, movement of electron, and transition state. The meaning that the transition state as a result of SN2 attack on the GTP structure was enacted. Since G protein was not part of the intra-activity, the meaning of its function was not articulated. The interviewer probed by explicitly asking about the role of G protein, enacting a space for potential new intra-activity. Bobby first responded that he had no idea, then proceed to speculate that its role would be either stabilizing the educt or providing energy to the product. The new intra-activities then produced the features stabilization and energy to differently enact the meaning of G protein function. In this new meaning, in addition to articulating the chemical change that was occurring with the substrate, G protein's role was also speculated.

Tracing signifying practices

Shifting the theoretical constructs to give voice to the context that oriented the semiotic features, I understood the practice of electron arrow pushing as a participant in the articulation of the different features that enacted the meaning of G protein function. For example, the meaning of the words "SN2 attack" was enacted through entangling the practice of arrow pushing with the external representation. Bobby started by describing that the SN2 attack began "originally with the OH_2 group". Then, the order of the features that become articulated traced the movement of the electron: “the phosphate, and then the proton here gets kicked or kicks its electrons onto the oxygen, onto the phosphorus, and then kicks off the GDP group…then you have your product”. In the process of tracing the movement of electrons with the practice of electron arrow pushing, the structure of the substrate become intelligible within the interview space.

Although the interviewer directly introduced the word “G protein” into the interview space, the word did not intra-act with other features articulated through the practice of electron arrow pushing. Bobby first expressed that he “had no idea” about the role of the G protein, relating G protein to the other features through the difference between what was known and what was unknown: the features that intra-act within the practice of electron arrow pushing were known, while those that cannot be articulated within the practice were unknown. The enactment of the boundary between the known and the unknown produced features within articulated intra-activities and features within speculated intra-activities.

Tracing the participation of materiality

Giving voice to the materiality of the external representation as a participant in the enactment of meaning, I understood the role of the reaction equation’s materiality as making the temporality of the reaction matter. The reaction equation was written in a way to be read from the left to right, a cultural norm of chemistry. The order of the reactants as they were written enacted a temporal meaning where the substrate took on the meaning of being present “originally” and water “comes in” afterwards. Although the presence of GTP and water in the cell is simultaneous, the meaning enacted by thinking with external representation also included the temporal order of the two educts. The reaction equation’s materiality may recall the context of organic reactions carried out in the laboratory, where reactants may be added in order to produce the reaction. The material practice of organic experiments and the cultural practice of writing from left to right were entangled to produce the materiality of the external representation as organizing the educts in order and enact the meaning of G protein function.

When Bobby was thinking with the reaction equation, G protein did not take on any materiality. It was only mentioned by the word of "G protein" in the interview handout. The words "educt", "transition state", and "product", on the other hand, were intra-acting with the chemical formulae and enacted a materiality for these words. They participate in the enactment of the meaning of G protein function while G protein was limited by the lack of enacted materiality. The role of G protein had few intra-actions with other features and was enacted within the intra-action with what is unknown. Similar to what was reported about the participation of the materiality of chemicals in chemistry teaching and learning, the materiality of external representations also participated in the enactment of the meaning of chemistry concepts.

Thinking with Cartoon Diagram

Following the intra-activity between Bobby and the reaction equation that enacted a meaning for G protein function, a cartoon diagram was available for Bobby to think with (shown below in Figure 5.2). The G protein was depicted in blue while the GAP was depicted in red. Segment 5.2 below shows the interview transcript excerpt when Bobby was asked about the features that he noticed in the cartoon diagrams. In this segment, the boundary was enacted to separate the external representation as the object.

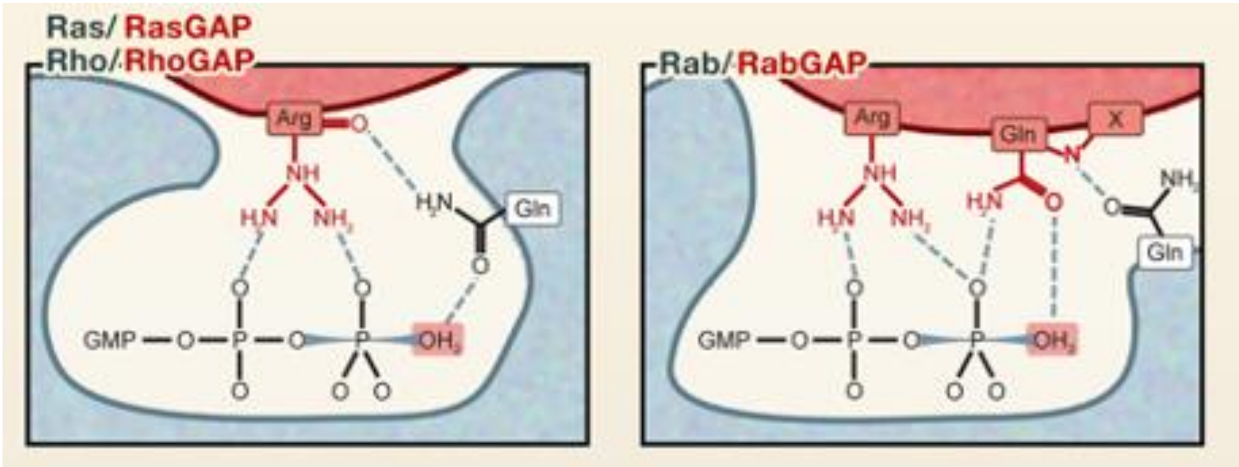

Figure 5.2: Cartoon diagrams of G protein complexes. On the left, a diagram of the Ras/RasGAP and Rho/RhoGAP complex was illustrated with G protein in blue and GAP in red. On the right, Rab/RabGAP complex was illustrated with the same color scheme.

Segment 5.2

> Interviewer: Could you describe what you see in the two diagrams?
> Bobby: This would be the active site here. The substrate comes here and binds with an active site. And there's just hydrogen bonding between the active site and the substrate, the hydrogens and the oxygens between the substrate and the active site. Both have the phosphorus group with the oxygens in this bent structure here. Both oxygens are coming up like this, from off the sides, so it's not entirely planar. We have the GMP which I assume is a precursor to the GDP or it's similar in nature. I'm not familiar with it either so I can't definitively say.
> Interviewer: What are some differences that you see between the two diagrams?
> Bobby: The OH_2 is already attached to the phosphorus, or it wasn't in the original task. Seems like the active site here is larger, which facilitates more amino acid interactions. This one has arginine and glycine. This one has two glycine and an arginine, and there's more hydrogen bonding between the two. This oxygen is stabilized by two hydrogen bonds as opposed to only one.

Tracing semiotic features

When tracing the semiotic features with cartoon diagrams of G protein, I noticed that Bobby expressed that both diagrams showed hydrogen bonding between the active site of the G protein and the substrate. Bobby then pointed out that the substrates in the two diagrams were similar and related the GMP shown in the diagrams to the GDP shown in the reaction equation by proposing that GMP is a precursor to GDP or similar to GDP. In addition, features also emerged when Bobby articulated the differences between the two diagrams. Bobby also articulated structural elements such as the specific amino acids that were present in the active site. The size of the active sites was also salient for Bobby. The active site in the Rab/RabGAP diagram was said to be bigger and "facilitates more amino acid interaction".

When the available external representations change, Bobby articulated new semiotic features. Compared to the features that were articulated when thinking with reaction equation, the features articulated with the cartoon diagram included more structural elements of the G protein. For example, active site was related to the substrate and hydrogen bond, enacting the meaning that the active site is where the G protein binds the substrate through hydrogen bonding. These features were enacted when Bobby intra-acted with the diagram but were not enacted when Bobby intra-acted with the reaction equation.

Segment 5.3 below shows the interview transcript excerpt when Bobby was asked to propose a model for G protein function with the cartoon diagrams. In this segment, the boundary was enacted to separate the external representation as participating as part of the subject while the meaning of G protein function is the object. The semiotic features that emerged in the previous segment were related with signifying practices to enact the meaning of G protein function differently. The materiality of the cartoon diagram also participated in the enactment of meaning.

Segment 5.3

> Interviewer: With these diagrams, how would you propose a model for G protein function?
> Bobby: Maybe the substrate comes in and interacts with an active site with the phosphorus and oxygens attached to the GAP. Um which can help kick off the transcription of the protein or something to that effect. I don't think this substrate can directly bind to the G protein, but it has phosphorus attached here which binds specifically to and then results in the production of the GAP. It can facilitate the production of that protein through transcription or translation. When they bind, they can have interactions where it's like reading an epitope within immunology. They can selectively bind to each and result in the G protein being active. They

> result in favorable interactions which could kick off the GMP over here or something to that effect. As we see in this part over here, the same or similar reaction. We just haven't talked a ton about how proteins get activated in class. I'm not familiar so these are mostly just guesses based off my prior knowledge in immunology and about reactions in general. Knowing more about how proteins are activated through binding between enzyme and substrate because we haven't really touched on any of that. Looking at how they bind, not what happens after they bind.

Tracing signifying practices

I noticed that when a set of cartoon diagrams became available to think with, it was proposed that the substrate enters the active site of the G protein, and the phosphorus and oxygen atoms on the substrate would interact with the active site of the G protein. The interaction between the active site and the substrate would then facilitate the production the GAP. After GAP was produced, it would selectively bind to the G protein and activate the G protein to have favorable interactions with the substrate and facilitate the hydrolysis of GTP. The features that enacted the meaning of G protein functions are substrate, active site, protein production, and favorable interaction.

With the reaction equation, electron arrow pushing was a prominent signifying practice that related and produced semiotic features. However, with the participation of the diagram, the signifying practices became reconfigured to modeling protein activation and oriented the semiotic features differently. Within this signifying practice, semiotic features such as active site, GTP structure, and binding were oriented to signify the production of protein rather than the movement of electron or stabilization of the transition state. For example, the relationship between GTP structure and specific binding in the active site was enacted to signify that there would be the production of GAP through transcription or translation. The production and activation of protein also produced the limitation of the cartoon diagram in signifying. The binding between the substrate and the enzyme signified that there would be activation and production of G protein, but as the diagram only made the binding itself visible, it is limited to only signifying what happened after GAP was already produced and activated, rather than the process of activation, as Bobby expressed that he would like to know "more about how proteins are activated through binding between enzyme and substrate".

Tracing participation of materiality

Giving voice to the materiality of the cartoon diagram, I saw that the G protein complex took on materiality. This materiality participated in the production of semiotic features related to both the structure of the G protein and the interactions between G protein and substrate. For example, active site was a new feature that became salient when Bobby was thinking with the cartoon diagram. Considering the materiality of the carton diagram, the active site was given the most materiality: not only the structural elements of the G protein were related to the enactment of the active site, the empty space (where the substrate would bind) was also related to active site. These materiality of the diagram orients active site as the prominent new feature.

The participation of the materiality of cartoon diagrams also oriented what was not included in the materiality, and hence did not matter. In this sense, when moving from reaction equation to cartoon diagram, the materiality of the transition state was reproduced, but the materiality of the educt and product was not. The reproduction of the materiality of the transition state along with structural elements of G protein participated in the enactment of the meaning of G protein function as binding with the transition state.

Thinking with AR model

Following intra-activity with cartoon diagram, the AR model was available for Bobby to think with (shown below in Figure 5.3). The grey model depicts G protein without binding with GAP, and the pink model depicts G protein bound with GAP. Segment 5.4 below shows the interview transcript excerpt when Bobby was asked about the features that he noticed in the cartoon diagrams. In this segment, the boundary was enacted to separate the external representation as the object.

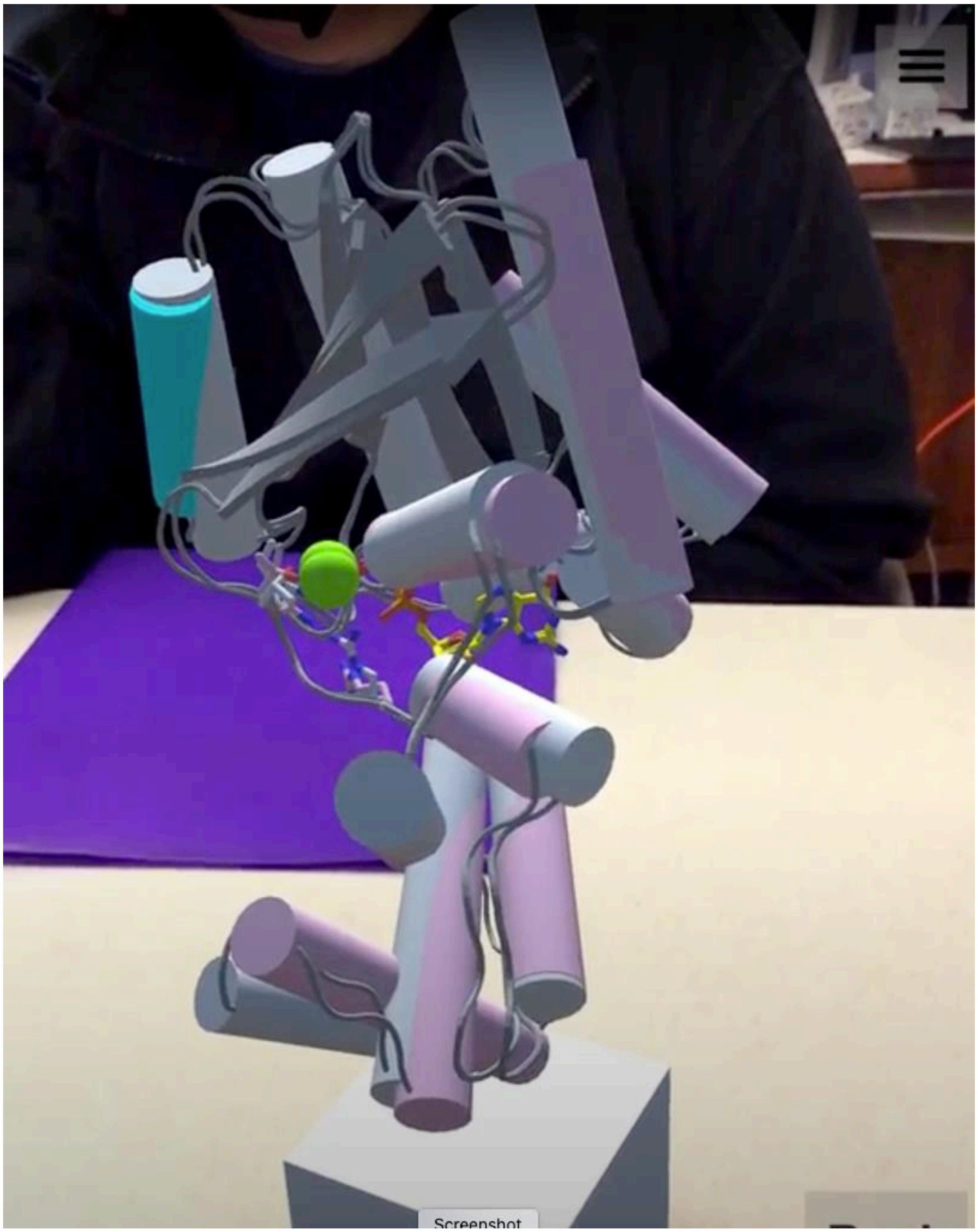

Figure 5.3: AR model of G protein. The grey model depicts G protein without binding with GAP, and the pink model depicts G protein bound with GAP.

Segment 5.4

> Interviewer: What do you notice from the AR models?
> Bobby: There's a lot more alpha helices than beta sheets, probably 15 alpha helices and only 5 beta sheets. In the middle, you can see the active site with all the amino acids. The polar... I'm not entirely sure what they are. There are loops as well. There is the magnesium ion as the bright green sphere. Seems like the active site might be a little different. Seems like the active site is more open so it's a little easier binding. And then closes or shifts to a more closed state where the active site is not as easily accessible after the binding of the GAP. I just focused on where that magnesium ion is and the amino acids within the active site. They seem a lot more... the beta sheets and the alpha helices are further apart from it. And then, they seem to condense in that area, as opposed to the original model. Well, the first one is able to bind to the GAP protein, and then in the second model, it's already bound so it's no longer able to continue binding to the GAP protein. That's why it closes off.

Tracing semiotic features

In the segment above, I first saw that Bobby noticed structural elements of the G protein (i.e., alpha helices, beta sheets, and loops) and the difference in their quantity. Bobby then suggested that the active site seemed to be different between the two overlayed models. Bobby suggested that the active site seemed "more open" when G protein was not bounded with GAP and then shifted to "a more closed state where the active site is not as easily accessible" when bounded with GAP. Focused on the location of the magnesium ion and the amino acids within the active site, Bobby suggested that the beta sheets and alpha helices of the G protein became condensed in the active site area after binding GAP to close off the active site.

When the available external representations change, Bobby articulated new semiotic features. Compared to the features that were articulated when thinking with reaction equation and cartoon diagram, the features that Bobby articulated with the AR model included the alpha helix and beta sheet structures of the G protein. For example, active site was related to the distance and spatial orientation of the alpha helices and beta sheets, enacting the meaning that the active site would change its shape to shift from binding the substrate to forming products. These features were enacted with the AR model but were not enacted with the reaction equation and the cartoon diagram.

Segment 5.5 below shows the interview transcript excerpt when Bobby was asked to propose a model for G protein function with the AR model. In this segment, the boundary was enacted to separate the external representation as participating as part of the subject while the meaning of G protein function is the object. The semiotic features that emerged in the previous segment were related with signifying practices to enact the meaning of G protein function differently. The materiality of the AR model also participated in the enactment of meaning.

Segment 5.5

> Interviewer: How do you think the GAP will facilitate the activity of this G protein?
> Bobby: I think it's something with the glycine that could be hydrogen bonding between the active site and GAP protein to facilitate that conformational change. It'll come in. It'll hydrogen bond to the arginine and glycine here, rather than on the original complex. And then that will activate a conformational change to close off the active site. I originally proposed that it shifted over, which would make it larger, but it's just making it closed, something to that effect. The GAP protein would come in with the glycine and hydrogen bond with this arginine possibly here and here, here, and here. And that could possibly change the conformation of where the arginine is. So maybe the arginine could hydrogen bond to this oxygen here. I was going to propose that the glycine would come in and bind to these two spots. They would bind to here and here, and that could shift the hydrogen bonding from here to here, from this arginine, which would activate the active site and signal the conformational change, closing off the activation site so nothing else can come in and bind. Looking at the orientation of the beta sheets and the alpha helices and the active site within the model, it seems like the active site closed in on it itself, making a tighter bond. When it has that, it'll shift to formation of products rather than trying to bind to a protein. The enzyme substrate complex will then form a product as opposed to trying to bind to a substrate.

Tracing signifying practices

When AR model became available to think with, I noticed that conformational change in G protein was proposed to be induced by the hydrogen bonding between the active site of the G protein and GAP. The conformational change would then close off the active site of the G protein to “make a tighter bond”, which would then lead to the formation of products.

In this segment, the semiotic features of the external representation were related together within the practice of signifying structure-activity relationships to reconfigure the enactment of G protein function’s meaning. For example, the relationship between hydrogen bonding in the active site and the spatial orientations of the alpha helices and beta sheets was enacted to signify that there would be a conformational change when G protein binds GAP. The conformational change in turn signified that the function of the G protein would change to “make a tighter bond” within its active site. As the active site “close itself off”, the function of the G protein shifted from binding the GAP to forming the product.

Participation of materiality

Giving voice to the materiality of the AR model, I saw that both the bounded and the unbound version of G protein took on virtual materiality realized through super imposing a virtual object onto a real object. The AR model enacted materiality of structural elements such as alpha helices and beta sheets in addition to the amino acids that form the active site. The additional materiality participated in the enactment of the meaning of G protein function by positioning that the larger shape and conformation of the G protein also matter. For example, the orientation of the alpha helices and the beta sheets also mattered in addition to the shape of the active site when enacting the meaning of G protein function. As the spatial orientation of the alpha helices and the beta sheets change, the shape of the active site would change and “shift to formation of the products”.

The introduction of the AR model reconfigured the materiality of the interview space and made new intra-activity possible to enact meaning differently. For example, alpha helices and beta sheets were new features that emerged through intra-activity with active site. Through this intra-activity, the active site took on the materiality of alpha helices and beta sheets, and these structural elements also became meaningful in enacting the meaning of G protein function, i.e., their orientation determined the shape of the active site.

As the AR model was introduced in addition to the cartoon diagrams, the materiality of the cartoon diagram participated along the materiality of the AR model. In the diagram, hydrogen bonds had taken up the materiality of dashed line. The materiality of hydrogen bond continued to participate along with the spatial orientation of alpha helices and beta sheets to enact the meaning of G protein function. Rather than intra-acting within the practice of modeling protein activation, the materiality of hydrogen bond participated within the practice of modeling structure-activity relationship and intra-acted with the feature of conformational change.

SF of Interview with Bobby

Figure 5.4 below traces the intra-activities that enacted the meaning of G protein function during the event where Bobby was thinking with different external representations while answering a series of interview questions. As the analysis presented above constituted narratives that privileged one theoretical construct and one type of external representations over the others, the figure was produced by relating the researcher's narratives about semiotic features, signifying practices, and the materiality of the external representations. The production of the figure contributes to research reflexivity by attempting to give voices without privileging one theoretical construct over others. The connections between the different features traces the relation within which the two features become mutually constituted and articulated. For example, relating amino acid and active site articulate both features: the feature of amino acid took on the meaning of being a structural element of the active site, while simultaneously the feature of active site took on the meaning of being made of amino acids. Through this process of mutual articulation and constitution, new semiotic features emerged, and the meaning of G protein function become differently enacted.

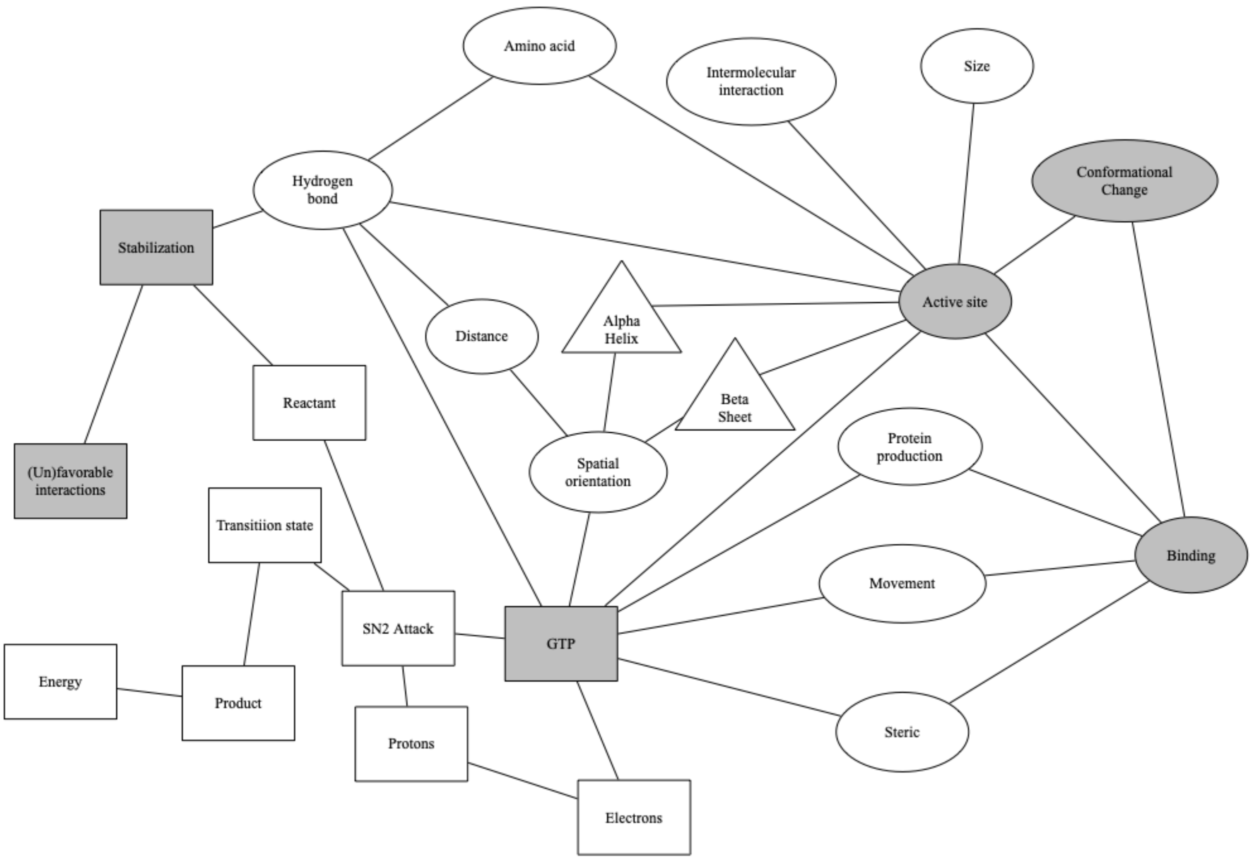

Figure 5.4: SF from tracing the intra-activity among semiotic features emerged during the interview with Bobby. Rectangle features are those that emerged when thinking with reaction equation. Round features are those that emerged when thinking with cartoon diagram. Triangle features are those that emerged when thinking with AR model. The shading represents the continued participation of the features. Darker shaded features are those that were reproduced when thinking with different external representations.

As the materiality of the external representations reconfigured, new intra-activities within signifying practices differently produce semiotic features and re(con)figure their meaning. For example, the feature GTP, which was first produced when thinking with reaction equation, was related to steric when the materiality of the external representations reconfigured, and the cartoon diagram was introduced. The new intra-activity with the materiality of the cartoon diagram reconfigured the meaning of GTP to articulate the feature of steric. GTP took on the meaning as an example of bulkiness, and steric took on the meaning as a property of molecular structure.

The analysis presented in this chapter illustrated my tracing of the reconfiguration of the material-discursive-semiotic assemblage that differently enacted matter and meaning. When Bobby was thinking with the reaction equation, the meaning of G protein's function was enacted in relation to the change in the substrate's structure. When the cartoon diagram was introduced, the meaning of G protein's function was reconfigured to activating or producing GAP. When the AR model was introduced, the meaning of G protein's function was reconfigured again to facilitating tighter bonding with the transition state through conformational change induced by binding with GAP. The materiality of the external representation, the signifying practices, and the semiotic features were entangled in the enactment of the meaning of G protein's function.

Chapter 6: SF from Tracing Jessica's Interview Event

In this chapter, I will trace the material-discursive-semiotic assemblage that emerged during an event where different external representations of G protein were made available for Jessica to think with while answering a series of interview questions. The analysis will be presented in four sections. In the first section, I will trace the assemblage that emerged when a reaction equation was made available for Jessica to think with. In the second section, I will trace the assemblage that emerged when a cartoon diagram of G protein was made available for Jessica to think with. In the third section, I will trace the assemblage that emerged when an AR model of G protein was made available for Jessica to think with. And lastly, I will present an overall SF for the interview event with Jessica. The texts presented in this chapter are not meant to serve as an attempt to create a transparent, singular narrative about what "really" happened during the interview event with Jessica or what Jessica "really" had as his mental image. Instead, the texts presented in the findings are tracings of thoughts that were made possible to think with when engaging with the post-humanist performative perspective discussed in agential variation theory. The meaning of the findings emerged within the intra-action between the philosophical, theoretical, and methodological considerations and the text in this chapter.

Thinking with Reaction Equation

The external representation that was available for Jessica to think with is shown below in Figure 6.1. The reaction equation was depicted with the structural formulae of the educts, transition state, and products. Segment 6.1 below shows the interview transcript excerpt.

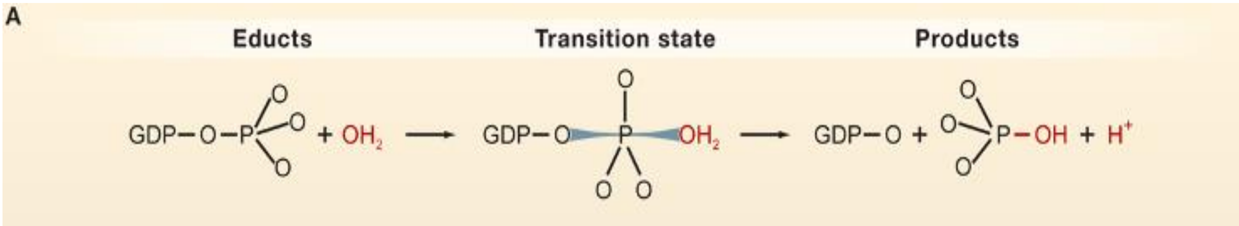

Figure 6.1: Reaction equation of GTP hydrolysis.
Segment 6.1

> Interviewer: Could you propose a model for G protein function?
> Jessica: I would imagine that a GTPase would stabilize the transition state, so probably facilitate the leaving of… This have a positive charge until the oxygen leaves, so I would think that something negatively charged is nearby. Perhaps it has something negative on it that could then stabilize the transition state, lowering the energy and facilitating that reaction to happen more quickly. Or it could have something to do with perhaps the shape of the GTPase holding, somehow binding some of these oxygens. These will be negatively charged or tend to hold electrons closer to them, so if it has amino acids that are polarizable, it may be able to hold this in a conformation that would allow this bond between P and the OH2 to form. That might be challenging since this is pretty bulky over here, especially if these are wildly swinging around, so it could be some kind of an enzyme that holds the oxygens in place and then allows this bond to form. I would think that it would probably have some polarizable amino acids in such a way that they would form intermolecular interactions with these oxygens, to sort of hold it in a specific conformation to prevent them from wildly swinging around because around a bond you can have movement, and that could create a space for this bond to form. There's a reason why the transition state is less stable, and I'm trying to figure out exactly why that is. It could just be steric. This is a really bulky thing, and it might be hard for this transition state to occur just because there're a lot of molecules all attached to the Phosphorus.

Tracing semiotic features

Tracing semiotic features with the interview segment above, I saw that Jessica proposed a model of the biochemical activities that could lead to the depicted changes in the structure of the substrate (i.e., hydrolysis). Jessica started with proposing a general process of GTPase activity: GTPase facilitated the hydrolysis of GTP by stabilizing the transition state of the hydrolysis reaction. From this starting point, Jessica reasoned that since the transition state will carry a positive charge until the oxygen leaves, a negatively charged "polarizable" amino acid would stabilize the positive charge on the transition state, thereby lowering the energy of the reaction and increasing the reaction rate. In addition to charge-charge interactions, Jessica reasoned that sterics may play a role in the stabilization of the transition state as well. Jessica suggested that the phosphate group on the substrate is bulky and would need the GTPase to “hold the oxygen in place” for the reaction to proceed.

With this segment, I understood the meaning of G protein function as enacted through the features stabilization, transition state, steric, charge, amino acid, movement, GTP structure, polarity, energy, and reaction rate. I saw the intra-activity among these features articulated as Jessica produced these features and enacted their meaning. The intra-action between the features GTP structure and binding opened the possibilities of the external representation’s meaning. Initially, the relationship between Jessica and the reaction equation was anchored around the stabilization of the transition state by GTPase. Additional intra-action extends this territory of learning to relationships between charge and electronegativity, energy and reaction rate, steric and bond formation.

Tracing signifying practice

Modeling structure-activity relationship was a prominent signifying practice that oriented the semiotic features. I saw that the biochemical activity of molecules was seen as determined by molecular structure. At the same time, biochemical activities can result in a change in molecular structure. The reflexive relationship between structure and activity guides the expansion of the meaning of GTPase. The starting point of the activity of GTPase was stabilizing the transition state. The structure of the GTPase (i.e., there would be negatively charged amino acid on the GTPase, the shape of the GTPase need to be in specific conformation) was articulated by orienting the structure of the transition state and the activity of the GTPase.

The reflexive reasoning about the structure and activity of GTPase focused primarily on two structural features: charge and steric. Jessica argued that the charge and steric of the substrate posed obstacles for the activity of GTP hydrolysis to occur, while the function of GTPase was to mitigate these challenges. Therefore, the structure of the GTPase must be able to facilitate the stabilization of the transition state by overcoming the bulkiness of the transition state and bringing complementary charges to proximity. Jessica expressed that "there is a reason why the transition state is less stable, and I am trying to figure out exactly why that is". This causal intra-action did not have a pre-existing cause and a pre-existing effect with which to form a causal interaction. Instead, the causal speculation is the pre-existing relation that produce both the effect (transition state being less stable) and the cause (steric and electronegativity) within the signifying practice of modeling structural-activity relationship.

Tracing the participation of materiality

Giving voice to the materiality of the external representation, I saw that the reaction equation participated in the enactment of meaning by making parts of the GTP structure matter. In the reaction equation, the materiality of the terminal phosphate group was different from the rest of the molecule. All atoms and bonds related to the terminal phosphate group took on materiality, while the rest of the molecular structure was obscured with "GDP" as their materiality. The materiality of the phosphate group participated in the enactment of the meaning of G protein function by contributing to the enactment of structural features of the GTP. For example, the materiality of the reaction equation enacted the meaning that the GTP structure is bulky, and the bulkiness of the structure signified that the activity of the G protein is to "hold" the GTP in a specific conformation to allow the bond between GTP and water to form.

The materiality of the phosphate group also participated in the enactment of the meaning of bulkiness when intra-acting with the feature of movement. On the reaction diagram, the bonds between the oxygens and the phosphorus took on materiality, and this materiality intra-acted with movement of the molecule to enact the meaning of bulkiness as having atoms “wildly swinging around” a bond. The feature “bulkiness” took on the meaning of not just the shape of the external representation, where the phosphate group took on a materiality disproportionate to the rest of the GTP structure, but also the movement of the atoms that could happen around the chemical bond.

Thinking with Cartoon Diagram

Following the intra-activity between Jessica and the reaction equation that enacted a meaning for G protein function, the cartoon diagram was available for Jessica to think with is (shown below in Figure 6.2). The G protein was depicted in blue while the GAP was depicted in red. Segment 6.2 below shows the interview transcript excerpt when Jessica was asked about the features that she noticed in the cartoon diagrams. In this segment, a boundary was enacted to separate the external representation as the object.

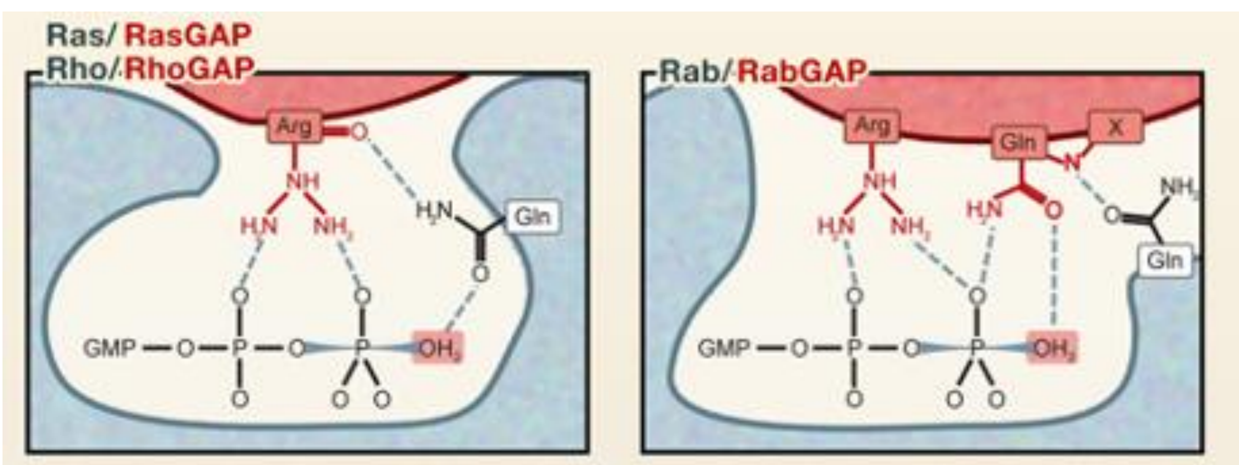

Figure 6.2: Cartoon diagrams of G protein complexes. On the left, a diagram of the Ras/RasGAP and Rho/RhoGAP complex was illustrated with G protein in blue and GAP in red. On the right, Rab/RabGAP complex was illustrated with the same color scheme.

Segment 6.2

Interviewer: Could you describe what you are noticing when looking at these two illustrations?

Jessica: I see that we have Arginine over here, which has its NH_2 group which tends to have positive charges, which seem to be interacting with the oxygens. And then there's also GLN, I forget what the full name for that amino acid is, but its carbonyl oxygen is interacting with the OH_2 over here and stabilizing the formation of that, because water doesn't want to grab it. That answered my questions a little bit about why the water molecule would bind the phosphorus here. That's not really favorable and it needs to lose a proton, but if it's stabilized with something that is electronegative or electron dense, that can stabilize that positive charge that forms over here. And then over here, I see now this NH_2 group also gets involved. We have some more intermolecular forces between nitrogen and oxygen.

Tracing semiotic features

When tracing the semiotic features with the cartoon diagram of G protein, I noticed that the introduction of cartoon diagram as part of the material-discursive-semiotic assemblage within which Jessica thought with the external representations articulated new semiotic features. Compared to the previous segment where Jessica was thinking with the reaction equation, new features such as "active site" and "NH_2 groups" emerged. These features describe a structural element of the features that emerged in the previous segment.

In the segment where Jessica was thinking with only a reaction equation, stabilization was first associated with the transition state. The relation between stabilization and transition state also produced the meaning of transition state has having a higher energy. In this segment, the relation between stabilization and transition state was specified to the oxygen atom of the transition state.

Segment 6.3 below shows the interview transcript excerpt when Jessica was asked to propose a model for G protein function with the cartoon diagrams. In this segment, the boundary was enacted to separate the external representation as participating as part of the subject while the meaning of G protein function is the object. The semiotic features that emerged in the previous segment were related with signifying practices to enact the meaning of G protein function differently. The materiality of the cartoon diagram also participated in the enactment of meaning.

Segment 6.3

> Interviewer: With these two illustrations, could you propose a mechanism for G protein function?
> Jessica: I would specify what I said before to say it looks like specifically NH_2 groups are what we have stabilizing the oxygen on the substrate from the active site on the GAP complex. I'm more inclined to believe this second image just because it seems to *have higher specificity for activation of the substrate, both having an NH_2 group near this oxygen that could interact as well as a carbonyl oxygen near the OH_2 group to help stabilize that bond there, and then eventually gets deprotonated.* I would tend to believe a mechanism more if it had a higher specificity based on what I've seen in class, because this seems general enough to me that I think there are multiple other amino acids that are probably bumping around that could do the same thing. So, for looking for specifically why a GAP stimulates GTPase activity, this seems to make more sense. It holds the molecule in a better conformation, and it doesn't let bending happen between this spinning around of this joint of this bond. I think it holds it in a better conformation with all of the different NH_2 groups. Over here this gets stabilized by a GLN that's on the G protein itself whereas here it gets stabilized by something that's coming in and doing it. If the GLN is too far to stabilize over here, it makes sense that it would be catalyzed then by something else coming in and being able to interact and stabilize the charge over here. Pretty much anything with an Arginine can just come in and bind these, and that's less believable because this is always being stabilized by something that's on the protein. So, to me, this won't work as well until you add this GAP complex, and then you're getting stabilization and formation of this OH_2 binding this phosphorus and if you lower like the energy of that whole step, then you can speed up the reaction.

Tracing signifying practice

Tracing signifying practices with cartoon diagram, I noticed that when two different diagrams of G protein/GAP complex were made available for Jessica to think with, a practice of signifying the specificity of active sites emerged. Although it was not part of the interview structure, the comparison of the two diagram was an emergent mode of intra-action within the interview space that enacted the meaning of G protein function. Instead of thinking with the two diagrams as referring to two different physical objects in nature, Jessica considered them as two potential models for G protein function and expressed that she would "tend to believe a mechanism more if it had a higher specificity based on what I've seen in class, because [seems general enough to me that I think there are multiple other amino acids that are probably bumping around that could do the same thing, so for looking for specifically why a GAP stimulates GTPase activity, this seems to make more sense".

Intra-action between features of G protein function within the practice signifying specificity of active sites enacted the meaning of the semiotic features and the meaning of G protein function. For example, the intra-activity between NH_2 group, stabilization, and deprotonation enacted the meaning that the Rab/RabGAP diagram illustrated a model for G protein function that had higher specificity. The structural elements of the active site as well as the interactions between the different structural elements were related together to signify the specificity of active site.

Tracing participation of materiality

With the introduction of cartoon diagrams, the materiality of the interview space was reconfigured, and new forms of intra-action happened. Giving voice to the materiality of the cartoon diagrams, I noticed that the presentation of the two cartoon diagrams side by side prompted Jessica to compare the two diagrams in terms of the specificity of the depicted protein. Without being prompted by the task instructions or interviewer questions, Jessica expressed that she would be more inclined to believe in the diagram of Rab/RabGAP more. She reasoned that the active site depicted in this diagram seem to have more specificity than the other. Explaining her reasoning further, Jessica suggested that Ras/RasGAP diagram seemed general enough that "anything with an Arginine" can also fulfill the function of the GAP. On the other hand, the

Rab/RabGAP complex seem to hold the GTP molecule in a better conformation where "there's the right distance there to stabilize this specific transition state".

The materiality of cartoon diagrams participated in the enactment of a model of G protein function with more added details about the structure of the protein. Instead of general statements such as "perhaps it has something negative on it that could stabilize the transition state", the materiality of the cartoon diagrams participated in the enactment of the meaning of the stabilization process with more detail, illustrated in the quote: "specifically NH_2 groups are what we have stabilizing the oxygen in the active site". When thinking with reaction equation, Jessica expressed "this have a positive charge until the oxygen leaves, so I would think that something negatively charged nearby... perhaps it has something negative on it that could then stabilize the transition state". With the diagram, the entities that participated in the stabilization took on the meaning of "NH_2 groups" and the location of these entities took on the meaning of active site. The materiality of the cartoon diagram participated in the enactment of meaning by contributing to differently labeling the entities that involved in the stabilization of the transition state.

Thinking with AR Model

Following the intra-activity with cartoon diagram, the AR model that was available for Jessica to think with is shown below in Figure 6.3. The grey model depicts G protein without binding with GAP, and the pink model depicts G protein bound with GAP. Segment 6.4 below shows the interview transcript excerpt when Jessica was asked about the features that she noticed in the AR model. In this segment, the boundary was enacted to separate the external representation as the object.

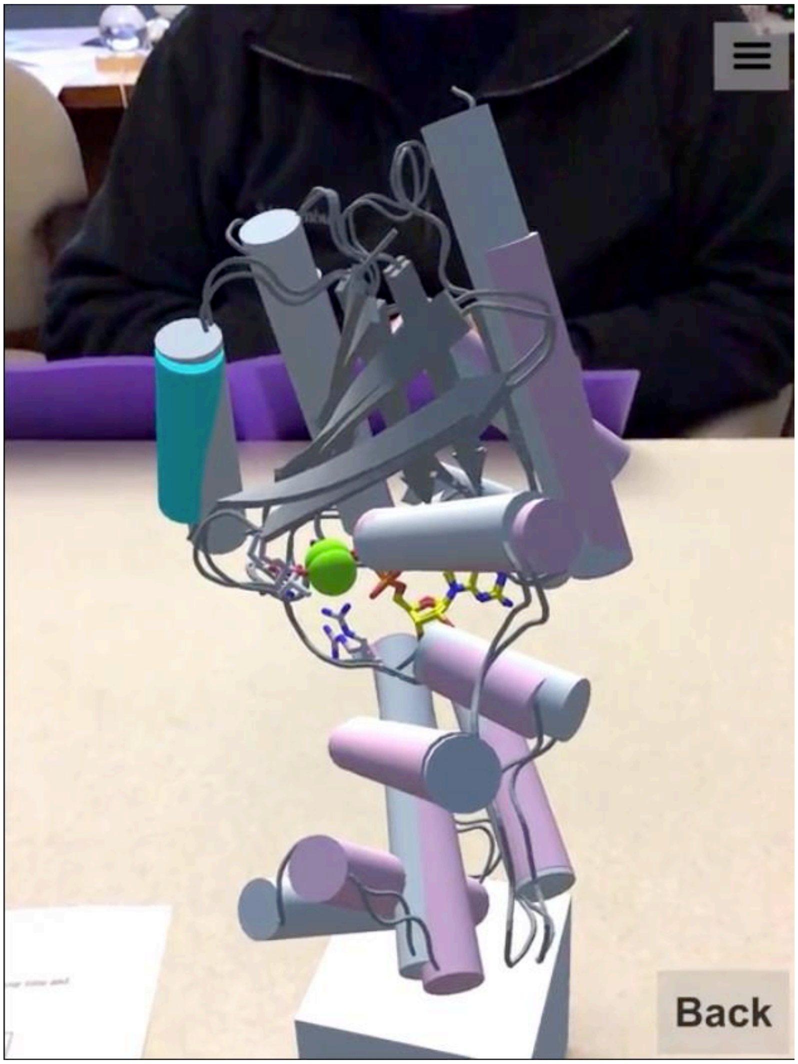

Figure 6.3: AR model of G protein. The grey model depicts G protein without binding with GAP, and the pink model depicts G protein bound with GAP.

Segment 6.4

Interviewer: Could you describe what you are noticing in the AR model?
Jessica: I'm seeing the protein shown above the cube. Those blocks are probably alpha helices. The cyan is a switch 2 helix, and dark blue is a switch 1 loop. GTP is sticks over here in the center. The G protein is huge and I'm seeing a tiny little substrate, or I'm seeing a tiny little GTP over here that binds and activates or speeds up the reaction. There's magnesium and then there's some other stick molecule in there. Residues important for catalysis are showing in pink and orange. They're showing sort of the rest of the protein around it and then we see the shape of the tiny little GTP in yellow. The yellow is what I'm proposing that binds up here, whereas and the pink is these carbons. The residues important for catalysis are on the G protein. I can see the arginine with its NH_2 groups. I can see the GLN amino acid interacting. I see some other amino acid with a carbonyl group also interacting with the magnesium. Only the substrate and the relevant side chains are in color. I'm seeing that the Arginine molecule changes its

> position from... we said unbound is pink right? Yeah, and then gray, so going from unbound to bound, it goes... I'll call neutral and looks like it's angling up a little bit more toward the magnesium ion and the rest of the substrate. It looks like the placement of the NH_2 groups changes as well as the position of the GLN, so both of them are pointed away from the OH_2 group and oxygen molecules here…in the unbound conformation, and when it gets bound they change their physical location and they're facing up or toward these molecules, which changes the distance between them, which I think could affect what's binding, or what's interacting with what.

Tracing semiotic features

In the segment above, I first noticed that when the AR model was introduced, Jessica articulated the structural elements of G protein such as alpha helices, loops, and the amino acids that were interacting with the substrate. She then expressed that there was a large difference between the size of the G protein and the size of the substrate. Comparing the bound and unbound versions of G protein model, Jessica noticed that the spatial orientation of the amino acids in the active site was different and reasoned that these differences may have implications for the interactions within the active site.

Similar to when Jessica was thinking with cartoon diagram, the amino acid side chains continued to be an articulated semiotic feature that intra-act with features such as binding. The introduction of AR model also produced new semiotic features about the structural elements of the G protein such as alpha helix and loop. In this segment, these new features of structural elements did not intra-act much with other features. For example, the feature alpha helices had intra-action with the materiality of the AR model (i.e., "the blocks"), but did not have intra-action with semiotic features such as spatial orientation, substrate, or conformation.

Segment 6.5 below shows the interview transcript excerpt when Jessica was asked to propose a model for G protein function with the AR model. In this segment, the boundary was enacted to separate the external representation as participating as part of the subject while the meaning of G protein function is the object. The semiotic features that emerged in the previous

segment were related with signifying practices to enact the meaning of G protein function differently. The materiality of the AR model also participated in the enactment of meaning.

Segment 6.5

> Interviewer: With the AR model, could you propose a mechanism for heterotrimeric G protein function?
> Jessica: There's probably a conformational change when GAP binds the G protein that is moving the relevant residues to probably a better place to interact and cause the hydrolysis. I would think that it could be binding way up here, but it's causing this conformational change and changing the placement of the specific amino acid and side chains, and the directions that they're pointing toward. The distance that amino acids are from one another impacts whether or not they can hydrogen bond with one another or having intermolecular forces. *They also create localized environments*. I'm seeing that in one of the confirmations versus another, you might have *two nitrogens that are closer together which create a positive environment that might attract oxygen or something to bind there.* It might be that the binding of the enzyme speeds up the reaction because *it induces conformational change that affects the little local environment in terms of charge and in terms of steric hinderance.* It could be that sterically once it binds, it moves. The protein is folding in such a way that some intermolecular forces between the GTPase and the GAP are causing the protein to fold slightly differently. Maybe there are some hydrophobic interactions or some positive-negative charge-charge interactions, but for whatever reason, it could even be a slight shift in those intermolecular forces between those two different proteins that caused folding to change and cascade down and affect the active site, even if it's not binding directly to the active site. So, it could be that it's binding something out here that we don't see at all. Also, I obviously did not know there was a magnesium there but that can help stabilize because it's pretty positive, so it can be stabilizing a bunch of oxygens here by being pretty close. It seems like the magnesium is right here [point at the center of the diagram] if I had to put it somewhere on this diagram. That would be my understanding. Something can be binding anywhere, and then that causes a conformational change of the protein to refold in such a way that Arginine and GLN are able to form these molecular interactions.

Tracing signifying practice

When the AR model became available for thinking with during the interview, I noticed that it was speculated that when GAP binds heterotrimeric G protein, a conformational change may occur and change the orientations of amino acid residues and the distance between them. These changes would "affect the little local environment in terms of charge… in terms of steric hinderance". These changes were oriented to articulate the meaning of conformational change as moving the amino acid residues to better positions for interacting with the substrate and "could be inhibiting the substrate from unbinding and becoming a free ligand". The influence of objects that are not directly shown in the AR model was also articulated, suggesting that "it could be that it's binding something out there that we don't see at all".

In this segment, the semiotic features were oriented within the practice of signifying change in local environment. For example, the features conformational change, charge, steric, and binding intra-act within the practice of signifying change in local environment to enact the meaning of G protein function. Within their intra-activity, the meaning of G protein function was enacted as changing the charge and steric hinderance of the local environment around the substrate to speed up the hydrolysis reaction. The features that enacted the meaning of G protein function within the signifying practice also became articulated. For example, charge and steric are articulated as properties of the local environment, and conformational change is articulated as a way to change the local environment.

Tracing participation of materiality

When the meaning of G protein function was enacted with participation from the materiality of the AR model, the active site took on the meaning of being the "local environment" as the larger protein structure took on materiality in the AR model. Compared to the cartoon diagram, where only the active site took on materiality, the AR model has its materiality extended to the whole protein, and the participation of this materiality enacted features that were not enacted with the cartoon diagram. For example, the relative size of the substrate and the protein was enacted by the materiality of the external representation. Jessica expressed that the substrate was "tiny" while the protein was "huge". The materiality of size in the AR model then contributed to the enactment of the meaning of local environment, i.e., the location where the "tiny" substrate was bound to the G protein.

The introduction of the AR model reconfigured the materiality of the available external representations and made new intra-activity possible to enact meaning differently. For example, protein folding was a new feature emerged through intra-activity with intermolecular interactions and conformational change. Through their intra-action, the materiality of the spatial orientation of the structural elements of G protein in the AR model participated in the enactment of protein folding as a change in the spatial orientation. The materiality of the spatial orientation in AR model participated in the enactment of protein folding as the change in the spatial orientation of the amino acids.

SF of interview with Jessica

Figure 6.4 below traces the intra-activities that enacted the meaning of G protein function during the event where Jessica was thinking with different external representations while answering a series of interview questions. As the analysis presented above constituted narratives that privileged one theoretical construct and one type of external representations over the others, the figure was produced by relating the researcher's narratives about semiotic features, signifying practices, and the materiality of the external representations. The production of the figure contributes to research reflexivity by attempting to give voices without privileging one theoretical construct over others. The connections between the different features traces the relation within which the two features become mutually constituted and articulated. For example, relating amino acid side chain and deprotonation articulate both features: the feature of amino acid side chains took on the meaning of being able to participate in deprotonation, while simultaneously the feature of deprotonation took on the meaning of changes in the amino acid side chains. Through this process of mutual articulation and constitution, new semiotic features emerged, and the meaning of G protein function become differently enacted.

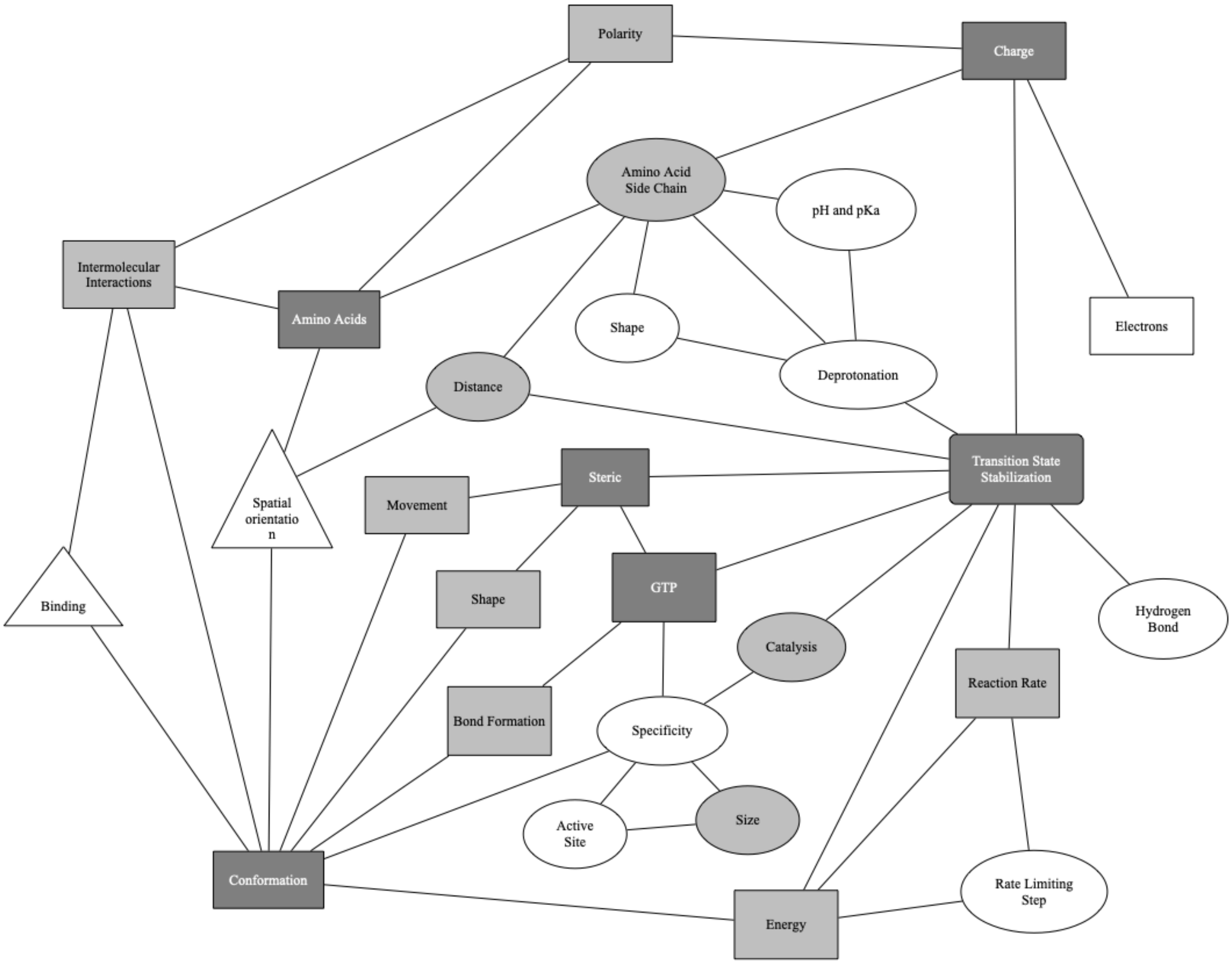

Figure 6.4: SF that trace the intra-activity among semiotic features emerged during the interview with Jessica. Rectangle features are those that emerged when thinking with reaction equation. Round features are those that emerged when thinking with cartoon diagram. Triangle features are those that emerged when thinking with AR model. The shading represents the continued participation of the features. Darker shaded features are those that were reproduced when thinking with different external representations.

As the materiality of the external representations reconfigure, new intra-activities within signifying practices differently produce semiotic features and re(con)figure their meaning. For example, the feature conformation, which was first produced when thinking with reaction equation, was related to specificity when the materiality of the external representations reconfigured, and the cartoon diagram was introduced. The new intra-activity with the materiality of the cartoon diagram reconfigured the meaning of conformation to articulate the feature of specificity. Conformation took on the meaning as having different levels of specificity, and specificity took on the meaning as a property related to the conformation of the amino acid side chains.

The analysis presented in this chapter illustrated the reconfiguration of the material-discursive-semiotic assemblage that differently enacted matter and meaning. When Jessica was thinking with the reaction equation, the meaning of G protein's function was enacted in relation to overcoming the steric of the substrate. When the cartoon diagram was introduced, the meaning of G protein's function was reconfigured to having high specificity with substrate and GAP. When the AR model was introduced, the meaning of G protein's function was reconfigured again to creating a local environment in the active site that would attract educts through conformational change induced by binding with GAP. The materiality of the external representation, the signifying practices, and the semiotic features were entangled in the enactment of the meaning of G protein's function.

Chapter 7: SF from Tracing Nicholas' Interview

In this chapter, I will trace the material-discursive-semiotic assemblage that emerged during an event where different external representations of G protein were made available for Nicholas to think with while answering a series of interview questions. The analysis will be presented in four sections. In the first section, I will trace the assemblage that emerged when a reaction equation was made available for Nicholas to think with. In the second section, I will trace the assemblage that emerged when a cartoon diagram of G protein was made available for Nicholas to think with. In the third section, I will trace the assemblage that emerged when an AR model of G protein was made available for Nicholas to think with. And lastly, I will present an overall SF for the interview event with Nicholas. The texts presented in this chapter are not meant to serve as an attempt to create a transparent, singular narrative about what "really" happened during the interview event with Nicholas or what Nicholas "really" had as his mental image. Instead, the texts presented in the findings are tracings of thoughts that were made possible to think with when engaging with the post-humanist performative perspective discussed in agential variation theory. The meaning of the findings emerged within the intra-action between the philosophical, theoretical, and methodological considerations and the text in this chapter.

Thinking with Reaction Equation

The external representation that was available for Nicholas to think with is shown below in Figure 7.1. The reaction equation was depicted with the structural formulae of the educts, transition state, and products. Segment 7.1 below shows the interview transcript excerpt.

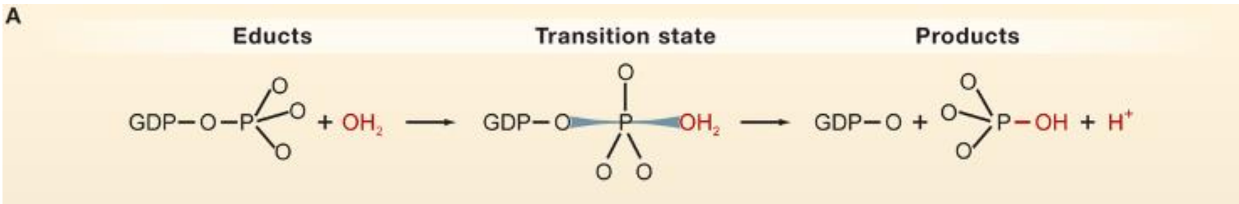

Figure 7.1: Reaction equation of GTP hydrolysis.
Segment 7.1

> Interviewer: With the reaction equation, could you propose a model for how G protein facilitate the hydrolysis of GTP?
> Nicholas: I think that you end up with water attaching onto the phosphorus somehow. Because it's an OH_2, you end up with one of the hydrogens leaving. I wasn't really sure about how you got the GDP and the oxygen coming off. I just have to hypothesize that GAP stabilizes the transition state here with the OH_2 positive. There're potentially negative amino acids in the active site somewhere around here and then it also somehow *cleaves off GDP and oxygen and then removes the hydrogen from the OH_2 positive*. Depending on the active site, it also potentially *provides an environment to bring together the two initial educts*. And since it's OH_2 positive here, that would have a positive charge on the transition state and could potentially make it slightly de-stabled. *You would want negatively charged amino acids over here to try to stabilize the positive charge*. Since you have oxygens here, you might see that would be pretty polar, so you might want a somewhat polar environment. I thought that GAP would bring together the educts and stabilize the transition state so that it would be more likely to go to products instead of either going back to educts or going to some other product. Providing an active site which is attractive to both educts can physically get them close to each other. Somehow the reaction cleaves off the GDP and the oxygen and remove the proton from the OH_2 positive here in the transition state going to the product. It probably just brings together the educts in one physical place since in order to have the reaction happen you have to have the molecules actually hit each other.

Tracing semiotic features

When Nicholas was presented with only the reaction formula of GTP hydrolysis, I noticed that he expressed his conception of G protein function focusing on the transition state of the reaction. Since the transition state was shown to have a positive charge, Nicholas hypothesized that the role of GAP was to stabilize the transition state with amino acids that have negative charges. Polarity was also mentioned as a property of the amino acids that may contribute to the stabilization of the transition state's positive charge. Overall, Nicholas proposed a model of G protein function where the G protein/GAP complex would bring the educts together, stabilize the positive charge on the transition state with negatively charged amino acids, and cleaves off the GDP to form the products.

The production of semiotic features started with articulating salient structural components of the product, namely the phosphorus group and the OH_2^+ group. Nicholas started his reasoning by thinking about the potential mechanisms that would lead to the leaving of OH_2^+ to form the product. He then hypothesized that the function of the G protein is to stabilize OH_2^+ so the group can then be cleaved off. In order to stabilize the positive charge on the OH_2^+ group, negatively charged amino acids must be present on the G protein. Nicholas also acknowledged that polarity can also contribute to the stabilization of the positive charge in addition to negatively charged amino acids. Tracing backwards from the stabilization of transition states, Nicholas argued that in order for stabilization to take place, the various educts must be first brought together to make it possible for "molecules to actually hit each other".

Tracing signifying practice

Shifting the theoretical constructs that I was thinking with to give voice to the context that oriented the semiotic features in their enactment of meaning, I came to an understanding that the semiotic features of the reaction equation were articulated through their intra-activity within the practice of signifying stabilization. Their intra-activities in turn contribute to the enactment of the meaning of stabilization. For example, features such as charge, transition state, and spatial proximity intra-act to enact meaning of stabilization as negatively charged amino acids on the active site stabilized the positive charge on the transition state and brought the educts to spatial proximity for the hydrolysis reaction to occur. In turn, the meaning of each feature was articulated through their intra-action with other features within the practice of signifying stabilization. For example, the meaning of charge was articulated as a property of amino acids that facilitate their interactions with the substrate to bring the educts to spatial proximity.

The meaning of G protein function was enacted within the practice of signifying stabilization. The structural elements of G protein such as active site and amino acids, and properties of these structural elements such as charge and polarity, intra-act to enact the meaning of G protein function within the practice of signifying stabilization. The charge and polarity of the amino acids in the active site enact the meaning of G protein function as stabilizing the transition state by through charge-charge interactions and polar interactions with the transition state of the substrate.

Tracing participation of materiality

Giving voice to the materiality of the external representation as a participant in the enactment of meaning, I saw the materiality of the external representation participated in the enactment of meaning by making the educts matter. In the reaction equation, the materiality of the educts consisted of two entities related by the plus sign. The materiality of educts participated in the enactment of the meaning of G protein function by contributing to the enactment of the structural feature spatial proximity. For example, the materiality of the reaction equation enacted the meaning that the educts need to be brought together, and the activity of the G protein is to "bring together the educts in physical space" so that the hydrolysis reaction can take place.

The materiality of the educts also participated in the enactment of the meaning of active site when intra-acting with the feature of charge. On the reaction diagram, the active site did not take on materiality, and intra-acted with the materiality of the educts to enact the meaning of the active site as having "an environment to bring together the two initial educts".

Thinking with Cartoon Diagram

Following the intra-activity between Nicholas and the reaction equation, the cartoon diagram was available for Nicholas to think with is shown below in Figure 7.2. The G protein was depicted in blue while the GAP was depicted in red. Segment 7.2 below shows the interview transcript excerpt when Nicholas was asked about the features that he noticed in the cartoon diagrams. In this segment, the boundary was enacted to separate the external representation as the object.

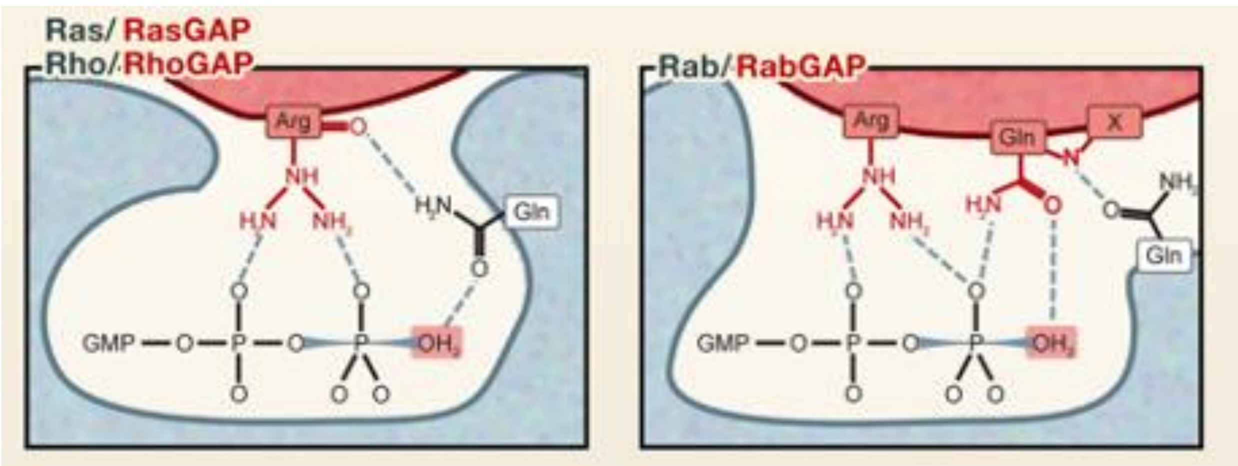

Figure 7.2: Cartoon diagrams of G protein complexes. On the left, a diagram of the Ras/RasGAP and Rho/RhoGAP complex was illustrated with G protein in blue and GAP in red. On the right, Rab/RabGAP complex was illustrated with the same color scheme.

Segment 7.2

> Interviewer: Here I have some example illustrations of G protein and GAP complexes. Can you tell me what you notice from these illustrations?
> Nicholas: Ok. For the GAP, I'm noticing that for both examples, they have an arginine in there that's interacting with the oxygens on one of the educts. And then for both of them, you have an oxygen from one source interacting with the OH_2 positive on the right side of the molecule. For both G proteins, there's a GLN over here on the right side of the active site that's being formed. For this one, the nitrogen atoms aren't really interacting with anything. But for this one, the hydrogens off the nitrogen atoms are hydrogen bonding with the oxygen up on the arginine. For both, the arginine sits approximately in the middle of the molecule, and the GLN is on the opposite side of the active site from the GMP. For both, the GAP complex is on top and the G protein on the bottom. One difference would be that this arginine has an oxygen sticking off the side of it while this arginine doesn't.

Tracing semiotic features

When the material-discursive-semiotic assemblage was reconfigured by the introduction of cartoon diagram as part of the external representations for Nicholas to think with, new semiotic features were articulated. When tracing the semiotic features with the interview segment above, I noticed that Nicholas expressed that both diagrams showed arginine interacting with the educt and oxygen stabilizing a positive charge. Nicholas then pointed out the spatial orientations between the structural elements of the G protein and GAP, and that there were hydrogen bonds forming between the amino acid on the G protein and the amino acid on the GAP.

The reconfiguration of the available external representations changed the intra-activities through which semiotic features were articulated, and the features became differently articulated. For example, the hydrogen bond was articulated through the intra-activity among hydrogen bond and amino acid side chains. Hydrogen bond took on the meaning as interactions between the nitrogen atom and the oxygen atoms, and the amino acid side chains of the G protein and GAP took on the meaning of binding with each other through hydrogen bonds.

Segment 7.3 below shows the interview transcript excerpt when Nicholas was asked to propose a model for G protein function with the cartoon diagrams. In this segment, the boundary was enacted to separate the external representation as participating as part of the subject while the meaning of G protein function is the object. The semiotic features that emerged in the previous segment were related with signifying practices to enact the meaning of G protein function differently. The materiality of the cartoon diagram also participated in the enactment of meaning.

Segment 7.3

> Interviewer: Now with this illustration, how would you propose a model for how the GAP and the G protein work to facilitate the hydrolysis of GTP?

> Nicholas: Here you have an oxygen stabilizing the positive charge on the OH_2. And you have other amino acids that are interacting with the oxygens. You have additional amino acids on top stabilizing the rest of the molecules. Based on the diagram, it looks like it's interacting with the amino acids through hydrogen bonding. Since the transition state noted inside these two illustrations have two phosphorus's while over here it has one, that would change things slightly but not dramatically, mostly results in more oxygens sticking off the phosphorus's that can interact with the amino acids coming off the GAP complex. Because of the longer molecule, you would end up with a slightly larger active site in order to fit it. But I think since it is a drawing, *everything is just drawn on the same plane so if there are any important amino acids behind that arginine, I'm not able to see it.* Since we're just using letters and lines for molecular structures, it's a little harder to see how the whole molecule looks like. The interactions between the molecule and the amino acids are more simplified since you just have a couple letters with dotted lines between them.

Tracing signifying practice

Tracing the signifying practices with the interview segment above, I notice that with the cartoon diagram available, it was proposed that the transition state was stabilized through hydrogen bonding with the amino acids in addition to the oxygen on the amino acids stabilizing the positive charge on the OH_2 group. The substrate illustrated in the diagram was a longer molecule and would require "a slightly larger active site in order to fit it" as the substrate would have "more oxygens sticking off the phosphorus".

The semiotic features of the reaction equation were articulated through their intra-activity within the practice of signifying fit between active site and substrate. Their intra-activities in turn contribute to the enactment of the meaning of fit between active site and substrate. For example, the feature transition state intra-act with the feature substrate and amino acid to enact the meaning of G protein function within the practice of signifying fit between active site and substrate. The two phosphate groups on the transition state would require a different active site to fit it in order for the G protein to facilitate the hydrolysis of the substrate.

Tracing the participation of materiality

Giving voice to the materiality of the cartoon diagram, I came to the understanding that the interview space was reconfigured with the introduction of the cartoon diagram and new intra-activities occurred. Compared to the reaction equation, two of GTP's phosphate groups took on materiality in the cartoon diagrams instead of one. This change in the materiality of the external representation participated in the enactment of the meaning that the substrate illustrated in the cartoon diagram was a longer molecule and would only fit into a larger active site. The same semiotic feature, i.e., the substrate, was enacted with different external representation and the materiality of the external representation enacted the materiality of the substrate within the practice of signifying fit between substrate and active site.

The materiality of the cartoon diagram also participated in the enactment of the meaning of G protein through constraining what was made visible. The materiality of the diagram enacted the meaning that all the semiotic features were made visible on the same plane, there could be structural elements that could have contributed to the enactment of the meaning of G protein function, such as amino acids that were not made visible. The constrain of the external representation's materiality enacted the meaning that there could be unseen structural elements that participated in fitting the substrate into the active site.

Thinking with AR Model

Following intra-activity with cartoon diagram, the AR model that was available for Nicholas to think with is shown below in Figure 7.3. The grey model depicts G protein without binding with GAP, and the pink model depicts G protein bound with GAP. Segment 7.4 below shows the interview transcript excerpt when Nicholas was asked about the features that he noticed in the cartoon diagrams. In this segment, the boundary was enacted to separate the external representation as the object.

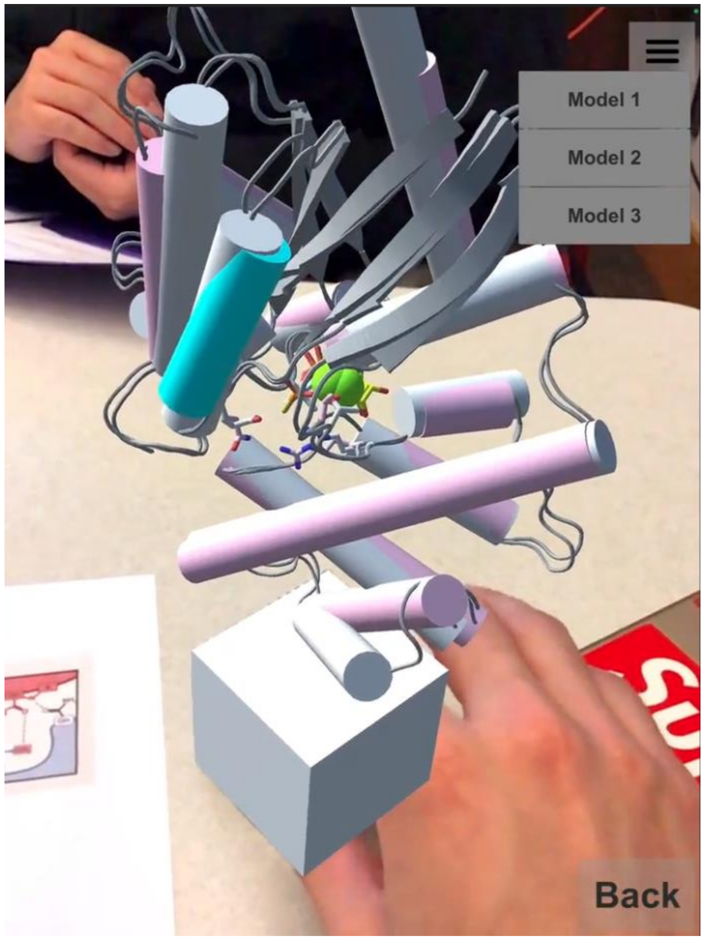

Figure 7.3: AR model of G protein. The grey model depicts G protein without binding with GAP, and the pink model depicts G protein bound with GAP.

Segment 7.4

> Interviewer: As you are getting familiar with the AR model, could you describe what you are seeing from the model?
> Nicholas: Yeah, sure. Starting off, there's a lot of lavender color. In the back there's a bit of cyan and blue. You can see the molecule and the active site sitting in the middle of the G protein complex. There's also a lime green ball. You can see that once you have the GAP regulator bound on, then you can see the slight conformational changes that the protein undergoes as it moves from the lavender color to the gray one. You can see some parts of the protein slightly shifting. You can see a couple alpha helices rotating a little bit. The bottom half of the molecule is primarily alpha helices and loops. And then the top half has an equal mix of beta sheets and alpha helices, and then a couple of loops forming between them. The area surrounding the active site seems to be a lot of loops primarily. There're a couple of alpha helices but it looks like it's mostly loops. There's one beta sheet near that active site that's dark blue, and then there's also an alpha helix near them that's kind of a cyan color. There is the molecule inside the active site.

> There're a couple of specific amino acids that are shown to be sticking into the active site pocket.

Tracing semiotic features

Tracing semiotic features with the segment above, I first noticed that Nicholas articulated the color of the AR model and the spatial orientation of the active site within the G protein when the AR model was introduced. The difference between the structure of the differently colored proteins made the conformational changes of the protein visible. Nicholas then articulated the structure of the protein as having mostly alpha helices and loops on the bottom and a mix of alpha helices and beta sheets on top. The alpha helices and beta sheets were surrounding the active site while the substrate was inside the active site where amino acids were "shown to be sticking into the active site pocket".

When AR model was introduced and changed the available external representations, new semiotic features can be enacted through reconfigured intra-activity. Compared to the features that were articulated when thinking with reaction equation and cartoon diagrams, semiotic features relating to the structure of the G protein such as alpha helix and beta sheet were articulated. For example, the intra-activity between alpha helix, beta sheet, spatial orientation, and active site articulated the meaning of active site as being in the middle of the protein surrounded by alpha helices and beta sheets. These structural features were not articulated when thinking with the reaction equation or the cartoon diagram.

Segment 7.5 below shows the interview transcript excerpt when Nicholas was asked to propose a model for G protein function with the AR model. In this segment, the boundary was enacted to separate the external representation as participating as part of the subject while the meaning of G protein function is the object. The semiotic features that emerged in the previous

segment were related with signifying practices to enact the meaning of G protein function differently. The materiality of the AR model also participated in the enactment of meaning.

Segment 7.5

> Interviewer: If you have to propose a model for G protein function with the AR model, what would be your idea?
> Nicholas: Reaction wise, would be similar to my old one, but now I would also have to look at my model and figure out what exactly is causing the conformational changes in the protein. *There is some extra hydrogen bonding here, which cause the protein to move this way and then that has an effect down the line throughout the entire structure of the protein.* I think inside the active site you still have this similar or the same amino acids stabilizing the transition state, but *once you have binding, then there're some conformational changes in the protein.* So, then *the molecule bound in the active site during the reaction would slightly change the shape of that protein.* So, then I would have to explain why parts of the protein are shifting over or shrinking down or popping up, and how that might influence parts of the reaction. I think once you have binding of a new molecule, then that interrupts some of the preexisting intermolecular forces and different bonds between the molecules in the protein. So then because those are altered, and the structure of the protein is mostly based off the reaction, once you tweak that a little bit, everything gets slightly shifted down the line. And it becomes physically too far away from another part of the protein to properly interact. Since the active site is taken up, and there have been conformational changes in the protein, you're not able to accept more reactant into the active site. So similar function but with additional consequences since in the diagram, for the G protein, it's just a blue blob so you can't really look at that and extrapolate how your blue blob would react in response to a GAP. With the AR model you can if you knew enough about biochemistry, and you had the amino acid sequence of the whole G protein. Then you can make more informed guesses on how the protein would change.

Tracing signifying practice

When AR model became available for Nicholas to think with, I noticed that the stabilizing interactions within the active site of the protein were suggested to be between the transition state and the amino acids but there are additional conformational changes in the protein that could be attributed to additional hydrogen bonding. When the G protein forms hydrogen bonds and binds with the substrate, its conformation would change, and the G protein would not be able to bind to more substrates.

In this segment, the semiotic features articulated with the AR model were oriented within the practice of signifying binding induced conformational change to reconfigure the enactment of G protein function's meaning. For example, the features intermolecular interactions, active site, binding, and conformational change intra-act within the practice of signifying induced conformational change. The meaning of G protein function was enacted through these features as undergoing a conformational change after binding the substrate to make the active site inaccessible to other reactants. The feature conformational change was articulated to be a consequence of binding the substrate.

Tracing the participation of materiality

Giving voice to the materiality of the AR model while thinking with the segment above, I came to understand that the materiality of the AR model participated in the enactment of the meaning of G protein function through contributing to the articulation of conformational change. For example, the materiality of the active site, the substrate, and the bounded and the unbound versions of G protein intra-act to articulate the conformational change was due to the binding of the substrate in the active site.

I also saw that the constrain of the materiality of the AR model contributed to the articulation of conformational change. For example, the GAP did not take on any materiality in the AR model, so the enactment of the meaning of G protein function was entangled with intra-action among conformational change, binding, intermolecular interactions, and substrate that articulated the meaning that the G protein functions by changing its conformation after the substrate binds and interrupts the existing intermolecular forces.

SF of Interview with Nicholas

Figure 7.4 below traces the intra-activities that enacted the meaning of G protein function during the event where Nicholas was thinking with different external representations while answering a series of interview questions. As the analysis presented above constituted narratives that privileged one theoretical construct and one type of external representations over the others, the figure was produced by relating the researcher's narratives about semiotic features, signifying practices, and the materiality of the external representations. The production of the figure contributes to research reflexivity by attempting to give voices without privileging one theoretical construct over others. The connections between the different features traces the relation within which the two features become mutually constituted and articulated. For example, relating hydrogen bond and substrate articulate both features: the feature of hydrogen bond took on the meaning of being formed between substrate and amino acid, while simultaneously the feature of substrate took on the meaning of binding to the active site through hydrogen bonding with amino acids. Through this process of mutual articulation and constitution, new semiotic features emerged, and the meaning of G protein function become differently enacted.

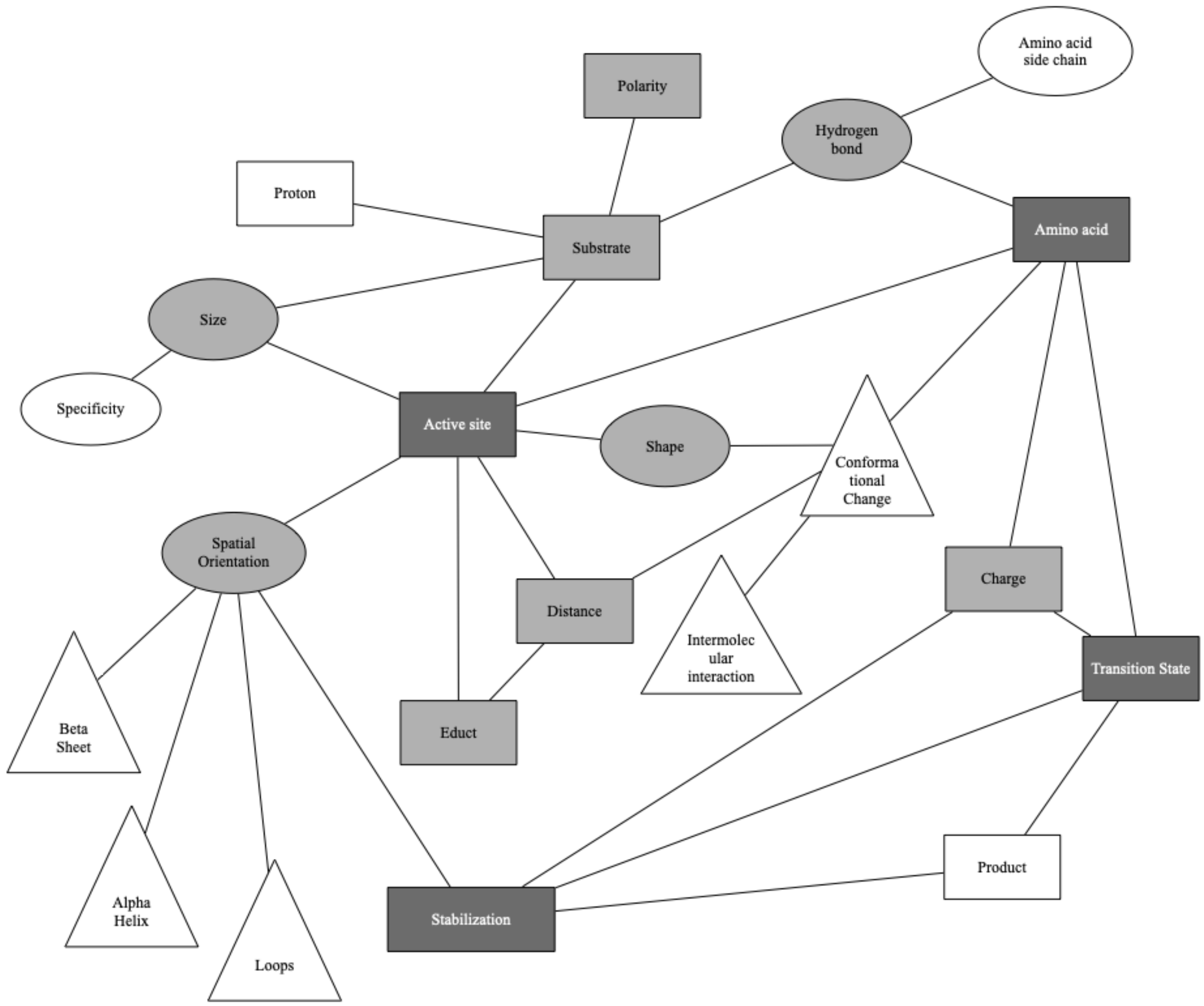

Figure 7.4: SF that traced the intra-activity among semiotic features emerged during the interview with Nicholas. Rectangle features are those that emerged when thinking with reaction equation. Round features are those that emerged when thinking with cartoon diagram. Triangle features are those that emerged when thinking with AR model. The shading represents the continued participation of the features. Darker shaded features are those that were reproduced when thinking with different external representations.

As the materiality of the external representations reconfigure, new intra-activities within signifying practices differently produce semiotic features and re(con)figure their meaning. For example, the feature shape, which was first produced when thinking with cartoon diagram, was related to active site, which was first produced when thinking with reaction equation. When the materiality of the external representations reconfigured again by the introduction of the AR model, the new intra-activity reconfigured the meaning of shape to articulate the feature of conformational change. Shape took on the meaning as not only in relation to active site, but also the broader conformation of the protein, and conformational change took on the meaning as a change in the shape of the protein.

The analysis presented in this chapter illustrated the reconfiguration of the material-discursive-semiotic assemblage that differently enacted matter and meaning. When Nicholas was thinking with the reaction equation, the meaning of G protein's function was enacted in relation to bringing together the educts and stabilizing the transition state. When the cartoon diagram was introduced, the meaning of G protein's function was reconfigured to fitting the transition state in the active site. When the AR model was introduced, the meaning of G protein's function was reconfigured again to influencing the hydrolysis reaction through conformational change induced by binding. The materiality of the external representation, the signifying practices, and the semiotic features were entangled in the enactment of the meaning of G protein's function.

Chapter 8: SF from Tracing Mary's Interview Event

In this chapter, I will trace the material-discursive-semiotic assemblage that emerged during an event where different external representations of G protein were made available for Mary to think with while answering a series of interview questions. The analysis will be presented in four sections. In the first section, I will trace the assemblage that emerged when a reaction equation was made available for Mary to think with. In the second section, I will trace the assemblage that emerged when a cartoon diagram of G protein was made available for Mary to think with. In the third section, I will trace the assemblage that emerged when an AR model of G protein was made available for Mary to think with. And lastly, I will present an overall SF for the interview event with Mary. The texts presented in this chapter are not meant to serve as an attempt to create a transparent, singular narrative about what "really" happened during the interview event with Mary or what Mary "really" had as her mental image. Instead, the texts presented in the findings are tracings of thoughts that were made possible to think with when engaging with the post-humanist performative perspective discussed in agential variation theory. The meaning of the findings emerged within the intra-action between the philosophical, theoretical, and methodological considerations and the text in this chapter.

Thinking with Reaction Equation

The external representation that was available for Mary to think with is shown below in Figure 8.1. The reaction equation was depicted with the structural formulae of the educts, transition state, and products. Segment 8.1 below shows the interview transcript excerpt.

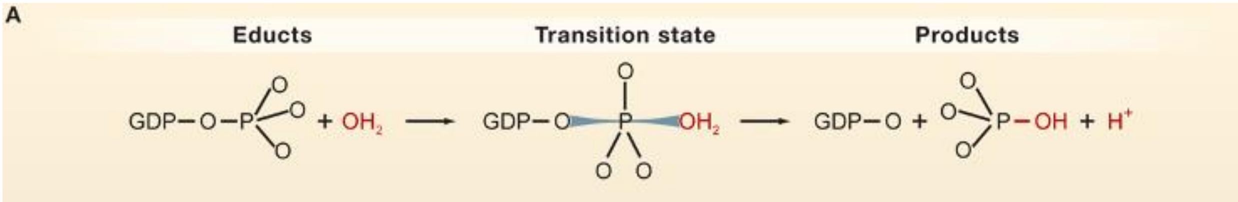

Figure 8.1: Reaction equation of GTP hydrolysis.

Segment 8.1

> Mary: Initially, my thoughts are that a lot of the times, enzymes work to stabilize a transition state. It looks like this chemical thing that's going on is a nucleophilic attack with the phosphate group and water. I would suggest that the enzyme would probably have an active site where water can enter in freely. But the GTP region is stabilized maybe with the phosphate group sticking out. And I think there are probably some charges on the phosphate, right? It's usually positively charged I think, which would allow the water to actually attack the phosphate. I'm not entirely sure. It's been a while since I took organic chemistry. But in terms of the enzyme function, I would suggest something like that.
> Interviewer: Could you say a little bit more about stabilizing the transition state?
> Mary: Yeah, okay. It looks like the product is releasing that phosphate group, so you would need to have the right amino acids in the area to make that possible. I'm trying to think of examples in class that we did too, but I'm kind of blanking. There are probably interactions with charged amino acid groups with the charged groups of the transition state in order to do that stabilization. I think that is probably a very generalized statement but also probably somewhat true. What we have learned in biochemistry is that a lot of what enzymes do is, like I said, that stabilizing process. And depending on where this molecule has a negative or positive charge, it may not be a favorable thing and that could lead to breakdown. Or it could lead to maybe more interactions with water or a different charged substance, rather than what you actually want or what the cell wants or what the enzyme wants... Not that they can actually think or anything but having those charged amino acids can block that effect from occurring with the interactions between the two, the substrate and the enzyme. And things like cyclic side groups also can do that stabilizing too, that we talked about, but I don't think that would be relevant in this case.

Tracing semiotic features

When thinking with semiotic features and the interview segment above, I first noticed that Mary started with reasoning that the common function of enzymes in general is to stabilize a transition state. Then, relating to the nucleophilic attack shown in the reaction equation, Mary suggested that the G protein functions by stabilizing the GTP in the active site where the phosphate group was "sticking out" for water to attack. When the interviewer asked Mary to elaborate on the stabilization of the transition state, she suggested that since the phosphate group needed to leave, charged amino acid groups would be needed to interact with the transition state to stabilize it and make phosphate leaving possible. Mary then argued that depending on the charge of the substrate, interactions with more water or other molecules might be occurring while the hydrolysis reaction was not favorable, and the charged amino acids on the active site of the G protein interacted with the substrate to prevent other molecules from reacting with the substrate.

In this segment, the meaning of G protein function was articulated by Mary through the features nucleophilic attack, stabilization, transition state, active site, GTP structure, charge, amino acid, and favorable process. The intra-activities among these features differently enacted their meaning. For example, the meaning of "stabilization of the transition state" was produced through the intra-activity between charge, amino acid, and favorable process. It was through articulating that charged amino acids can have favorable interactions with the substrate that the meaning of stabilizing the transition state became articulated. These intra-actions in turn enacted the meaning of amino acid as structural elements of the protein that contributed to the stabilization of the transition state, and the charge of these amino acid was the relevant property about these structural elements that enabled their participation in the stabilizing interaction.

Tracing signifying practices

Shifting the theoretical constructs to give voice to the context that oriented the semiotic features, I noticed that the practice of modeling structural-function relationship reconfigured the meaning of the semiotic features. The reaction equation was oriented towards depicting a nucleophilic attack, so there would need to be specific molecular structure in place to enable the function, i.e., an active site where water can enter freely. The nucleophilic attack signified that there would be a structure that facilitated the interaction between the two molecules that participated in the attack. In addition to nucleophilic attack, the function of releasing phosphate as a product also signified that there need to be “the right amino acids to make that possible”. The meaning of stabilizing the transition state took on meaning of bringing the educts together, then become reconfigured to have the additional meaning of having the required amino acids to release the product.

In addition to reconfiguring the meaning of semiotic features, relating structure and function together produced new semiotic feature that enacted the meaning of G protein function differently. For example, relating the function of stabilizing transition state to the structure of the active site produced the new features charged amino acid and charged substances, which enacted the meaning of G protein function as facilitating “interactions with charged amino acid groups with the charged groups of the transition state in order to do that stabilization”.

Tracing the participation of materiality

Giving voice to the materiality of the reaction equation, I noticed that the substrate was giving materiality in three different interactions. The reaction equation gave materiality to the substrate as educt, transition state, and product. The participation of these materiality directed the enactment of the meaning of G protein function to closely relate to the materiality of educt, transition state, and product. For example, the meaning of the reaction as a nucleophilic attack was first enacted with the participation of the materiality of the educt and the transition state, where two molecules were brought together to form the transition state. Then, with the participation from the materiality of the product, the meaning that G protein function would also facilitate the leaving of the phosphate group was also enacted.

The participation of the materiality of the reaction equation also oriented what is not included in its materiality. The structure of the G protein did not take on any materiality in the reaction equation, and the meaning of the structure of G protein was enacted through the signifying practice of structural-activity relation, going from the structure of the substrate to the function of the enzyme, and lastly to the structure of the enzyme. For example, the materiality of the transition state signified that charge-charge interaction would be a function of the G protein, which then lead to the speculation that the structure of the G protein contains negatively charged amino acids. Even though the reaction equation did not provide materiality for the structure of the G protein, the materiality it provided to the substrate participated in the enactment of the meaning of G protein structure.

Thinking with Cartoon Diagram

Following intra activity between Mary and the reaction equation, the cartoon diagram that was available for Mary to think with is shown below in Figure 8.2. The G protein was depicted in blue while the GAP was depicted in red. Segment 8.2 below shows the interview transcript excerpt when Mary was asked about the features that she noticed in the cartoon diagrams. In this segment, the boundary was enacted to separate the external representation as the object.

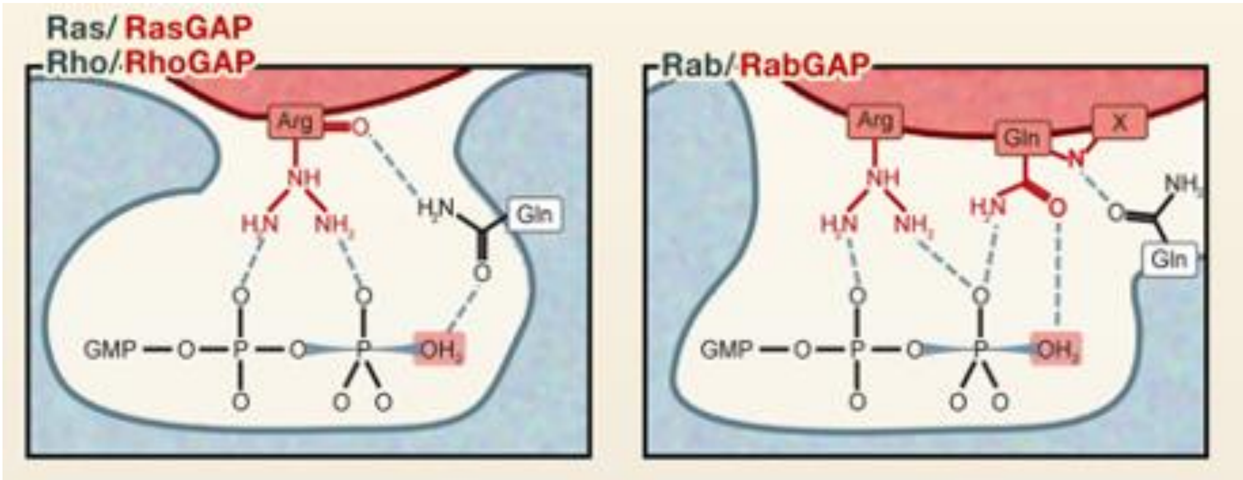

Figure 8.2: Cartoon diagrams of G protein complexes. On the left, a diagram of the Ras/RasGAP and Rho/RhoGAP complex was illustrated with G protein in blue and GAP in red. On the right, Rab/RabGAP complex was illustrated with the same color scheme.

Segment 8.2

> Interviewer: Could you describe what you're noticing in these two illustrations?
> Mary: Yeah. In this first image, which is the Ras and Rho proteins, it looks like there are these different stabilizing interactions between the carboxy group here in the pocket of the enzyme that are performing some stabilization of the transition state and the water specifically. The GAP has an arginine that is providing that stabilizing charge for the two oxygens on those phosphate groups. Similarly, in the Rab/GAP system, there are those charged arginine, and the other two glutamines. I think that's maybe glutamic acid, glutamine, glutamate, I don't know, but it looks like they have those charged portions of it that are able to stabilize that transition state. In the active site of the Rab and the Ras/Rho proteins, it looks like they both have the same side chains, but they are performing different interactions between the two GLN side group. Both GAPs also have the arginine, although on the first image, the image on the left, its carboxylate group is having an interaction whereas on the one on the right, it's not. They're all interacting with the same three atoms on the substrate, the oxygens of the phosphate group, as well as presumably attacking water. Shape-wise, it looks like these enzyme sites are different. Just based on these images, *the shape of the active site looks a bit different as well as what kind of side chains that are on the enzyme, and how it lines up with the active site.* In the image on the right, there are more interactions happening. It's maybe able to get a little closer because that active site is a bit more open. Whereas in the image on the left, that enzyme site looks a bit more contained, and there's only that one side chain interacting with the substrate rather than the two or three in the Rab enzyme.

Tracing semiotic features

When tracing the semiotic features with the cartoon, I first noticed the new semiotic features that were articulated to enact the meaning of G protein function. Mary discussed that in the first image, the carbonyl group on the G protein was contributing to the stabilization of the transition state by interacting with the water molecule while the arginine on the GAP contributed to the stabilization of the transition state. Mary suggested that the charged amino acids in the active site can provide a "stabilizing charge" to the oxygen atoms on the substrate. Mary also noticed that the shape of the active sites of the two diagrams were different, and the substrate might be able to have closer interactions if the shape of the active site was more open.

The reconfiguration of intra-activities among the semiotic features that occurred with the introduction of the cartoon diagram differently articulated the features. For example, the intra-activity among the features charge, amino acid, and active site articulated the active site as containing charged amino acid groups, similar to how the active site was articulated when the reaction equation was made available to think with. With the cartoon diagram, the feature active site also intra-act with shape, and articulated the active site as containing amino acids that were oriented differently due to their shape.

Segment 8.3 below shows the interview transcript excerpt when Mary was asked to propose a model for G protein function with the cartoon diagrams. In this segment, the boundary was enacted to separate the external representation as participating as part of the subject while the meaning of G protein function is the object. The semiotic features that emerged in the previous segment were related with signifying practices to enact the meaning of G protein function differently. The materiality of the cartoon diagram also participated in the enactment of meaning.

Segment 8.3

Interviewer: Now you have these two illustrations, how would you propose a model for how the protein stimulates the hydrolysis process of GTP?
Mary: The image on the left, that group is both interacting with the water and with the enzyme so maybe that's forming some sort of stabilizing complex between that GAP and the substrate in order to keep them close together potentially. And on the image on the right, that group the carboxylic oxygen is interacting with a nitrogen. I'm not sure what X is supposed to represent here, presumably just some other amino acid that has an exposed nitrogen. *It looks like it's performing a gluing effect.* It's trying to keep the two things close enough together in order for that enzyme to perform its stabilization and then ultimately allow the reaction to occur. I think what I was saying initially about the stabilizing effect of charged side groups is somewhat accurate, although now that knowing these details, *I can more accurately describe what exactly is happening and where exactly that stabilization is occurring*. Whereas before I might've just thought that it would happen on the third phosphate group, it actually appears that two of the phosphate groups on the GTP are being stabilized in order to break the two apart, which now that I think about it, it does make more sense because you're going to end up with two products. You probably want to be able to keep them both. You want to be interacting with both pieces of the final product so that makes sense to me. I'd say for GAP enzyme to stimulate hydrolysis, they interact with the active site of the G protein in a way in which they become close enough to the substrate, the GTP substrate. With their positively charged arginine side groups, they are able to interact with the oxygens of the phosphate groups in order to stabilize the transition state, which occurred after a nucleophilic attack of water to the terminal phosphate group of GTP.

Tracing signifying practice

Tracing the signifying practices that oriented the semiotic features, I noticed that when thinking with cartoon diagrams, the semiotic features of G protein function were oriented towards forming a stabilizing complex to keep the GAP and the substrate close together. This orientation contributed to the articulation that the interactions between the amino acids on the G protein/GAP complex and the substrate happened on two phosphate groups, and these interactions helped keep both of products of hydrolysis. The close distance between the G protein and the substrate, along with the positively charged amino acids in the active site, contributed the formation of interactions between the oxygen atoms of the substrate's phosphate groups and the active site to stabilize the transition state that occurred as a result of nucleophilic attack.

The practice of signifying molecular interactions related the semiotic features together in the enactment of the meaning of G protein function. For example, the feature active site was articulated within the intra-activities that enact the signifying relationship between the external representation and molecular interactions. Active site was related to distance, charge, and stabilization to articulate that the active site stimulates hydrolysis by being in close distance with the substrate and GAP so that charge-charge interactions can stabilize the transition state.

Tracing the participation of materiality

Giving voice to the materiality of cartoon diagram, I noticed that the reconfiguration of the external representation's materiality participated in the enactment of G protein's function by making more interactions between GTP and G protein/GAP complex matter. When Mary was thinking with the reaction equation, the meaning of stabilizing interactions was enacted within the limit of only between the terminal phosphate group and the active site. The cartoon diagram then reconfigured the materiality of external representations and the two phosphate groups and their interactions within the active site took on materiality. The materiality of the diagram contributed to the articulation of the interactions between the substrate and the active site to include interactions with the non-terminal phosphate group as well.

Thinking with AR Model

Following intra-activity with cartoon diagram, the AR model was made available for Mary to think with (shown below in Figure 8.3). The grey model depicts G protein without binding with GAP, and the pink model depicts G protein bound with GAP. Segment 8.4 below shows the interview transcript excerpt when Mary was asked about the features that she noticed in the cartoon diagrams. In this segment, the boundary was enacted to separate the external representation as the object.

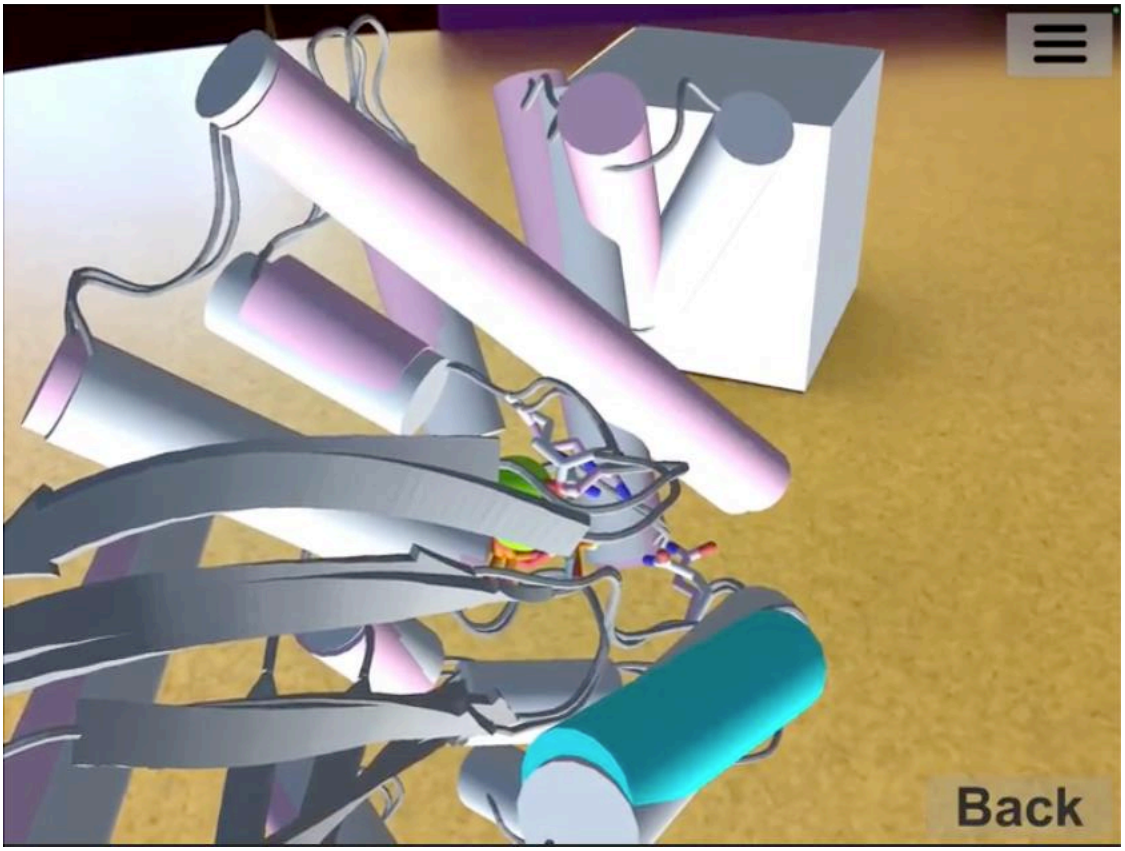

Figure 8.3: AR model of G protein. The grey model depicts G protein without binding with GAP, and the pink model depicts G protein bound with GAP.

Segment 8.4

> Interviewer: With the AR model, could you describe what you are seeing?
> Mary: Okay, a lot of pink, I think there's some cyan which refers to switch two helix. A little bit of blue. You have the green sphere which is magnesium. There're some side chains being bound to the magnesium. That looks like there's the GTP molecule interacting with a magnesium ion and it's all present within this G protein. It looks like *they're using that magnesium ion in order to stabilize negative charge,* I would assume. It seems like these residues are really close to that magnesium and maybe even a bit closer to that terminal phosphate group. There are also two distinctly different loops that are indicated by color. One is just the one gray protein whereas the the pink indicates the other thing. It has the loop and the helix regions, which I suppose is a difference that could indicate something as well. I guess loop regions are supposed to be maybe a bit more flexible. So, it could indicate that that's maybe the region of conformational change, although I can't be sure about that. You can see that the terminal phosphate group is in the motion of being pulled off closer to those residues. I think that's arginine. The arginine group seems closer to the charged oxygen regions of the terminal phosphate, which could serve to stabilize that transition state even further because there could be a stronger interaction occurring there.

> That gray arginine is pointed upwards, so it's pointed up towards that GTP, whereas in the pink one, its downwards, or it’s facing a different direction.

Tracing semiotic features

When tracing the semiotic features with the interview segment above, I first noticed that Mary articulated the color of the model, the magnesium ion, and the amino acid side chains that were interacting with the magnesium ion. Mary then suggested that the GTP molecule was also interacting with the magnesium ion, and the G protein was using the magnesium ion to stabilize the negative charge on the substrate. After noticing the two “distinctly different loops that are indicated by color”, Mary suggested that the loops could indicate conformational change as the loop structure is more flexible. Mary also suggested that the terminal phosphate group of the GTP was shown to be “pulled off closer” to the amino acid residues in the active site. The close distance between the arginine group and the terminal phosphate also resulted in stronger interaction between them and stabilize the transition state further.

When thinking with the AR model, new semiotic features such as conformational change and magnesium ion became articulated through their intra-action with other features, and existing semiotic features became differently articulated as a result as well. For example, the feature magnesium ion was articulated in relation to stabilization of negative charge and interaction with GTP molecule. Through these intra-actions, the meaning of magnesium ion became articulated as being used by the G protein to stabilize the negative charge on the substrate.

Segment 8.5 below shows the interview transcript excerpt when Mary was asked to propose a model for G protein function with the AR model. In this segment, the boundary was enacted to separate the external representation as participating as part of the subject while the meaning of G protein function is the object. The semiotic features that emerged in the previous

segment were related with signifying practices to enact the meaning of G protein function differently. The materiality of the AR model also participated in the enactment of meaning.

Segment 8.5

> Interviewer: With this new model, could you give an overview of your model of how this hydrolysis process works?
> Mary: Yeah. So especially compared to the images that I had seen, there was no indication of this magnesium ion which seems to perform a very essential task in stabilizing a lot of the negative charges that would be present on those phosphate groups. So that would lower the energy of that transition state, which is, again, the goal of an enzyme. *And it seems like the proteins are formed in such a way as to make that magnesium binding possible, so that is an important part of their function that wasn't shown on the pictures*. On the diagram of the reaction, there's no indication of that. And the idea of conformational change inducing the hydrolysis; you can see between the two models that there are some differences between the locations of the amino acids, which could indicate that that's how that conformational change takes place. Maybe there's the moving of an amino acid from being pointed upwards to being pointed downwards, and therefore pulling off the phosphate group or performing some other... maybe not function, but changing up that interaction in a way that would favor the hydrolysis and ultimately creation of the two products.

Tracing signifying practice

When the AR model became available to think with for Mary, I noticed that the magnesium ion was oriented as an essential part of stabilizing the negative charge on the substrate. In addition to the stabilizing effect, the magnesium ion would lower the transition state's energy, the conformational change of the G protein would change up the location and spatial orientation of the amino acids to favor the hydrolysis of the substrate.

In this segment, the practice of signifying molecular interactions oriented the semiotic features together to articulate the meaning of G protein function with more details. The introduction of the AR model reconfigured the available external representations, and the practice of signifying interaction with magnesium ion related the semiotic features together to differently enact the meaning of G protein function. The re(con)figure of the semiotic features was anchored around interaction with the magnesium ion. For example, the relation among charge, substrate, energy, and stabilization were enacted to signify that the magnesium ion stabilized the negative charge on the substrate. Within this practice, the AR model signified the interactions with the magnesium ion.

Tracing the participation of materiality

Giving the materiality of AR model voice as a participant in the enactment of meaning, I first noticed that the additional structural details of G protein took on virtual materiality realized through super imposing a virtual object onto a real object. The AR model enacted materiality of structural elements such as the spatial orientation of amino acids that form the active site and the presence of the magnesium ion. The additional materiality participated in the enactment of the meaning of G protein function making the magnesium ion also matter. For example, the charge-charge interaction between the magnesium ion and the substrate also mattered in addition to the charge-charge interaction between amino acid side chains and the substrate.

The introduction of the AR model reconfigured the materiality of the interview space and made new intra-activity possible to enact meaning differently. For example, magnesium ion was a new feature that emerged through intra-activity with the substrate and the G protein. Through this intra-activity, the G protein function took on the meaning of utilizing magnesium ion to facilitate the stabilization of the transition sate.

As the AR model is introduced in addition to the cartoon diagrams, the materiality of the cartoon diagram participated along the materiality of the AR model. The intra-action between what was shown in the diagram and what was shown in the AR model articulated the magnesium ion as an essential participant in the articulation of the meaning of G protein function.

SF of Mary's Interview Event

Figure 8.4 below traces the intra-activities that enacted the meaning of G protein function during the event where Mary was thinking with different external representations while answering a series of interview questions. As the analysis presented above constituted narratives that privileged one theoretical construct and one type of external representations over the others, the figure was produced by relating the researcher's narratives about semiotic features, signifying practices, and the materiality of the external representations. The production of the figure contributes to research reflexivity by attempting to give voices without privileging one theoretical construct over others. The connections between the different features traces the relation within which the two features become mutually constituted and articulated. For example, relating amino acid and active site articulates both features: the feature of amino acid took on the meaning of being a structural element of the active site, while simultaneously the feature of active site took on the meaning of being made of amino acids. Through this process of mutual articulation and constitution, new semiotic features emerged, and the meaning of G protein function becomes differently enacted.

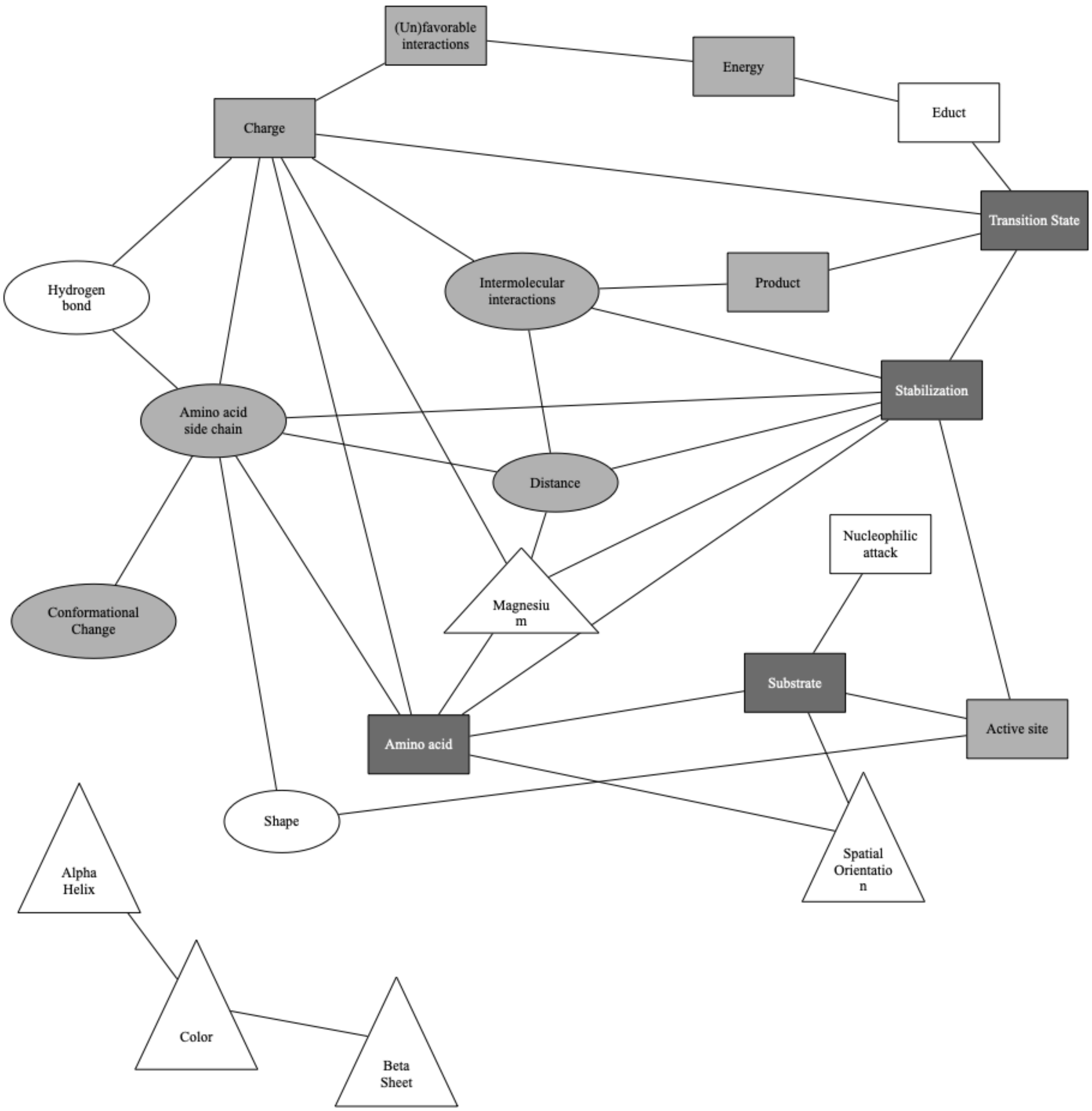

Figure 8.4: SF that traces the intra-activity among semiotic features emerged during the interview with Mary. Rectangle features are those that emerged when thinking with reaction equation. Round features are those that emerged when thinking with cartoon diagram. Triangle features are those that emerged when thinking with AR model. The shading represents the continued participation of the features. Darker shaded features are those that were reproduced when thinking with different external representations.

As the materiality of the external representations reconfigure, new intra-activities within signifying practices differently produce semiotic features and re(con)figure their meaning. For example, the feature product, which was first produced when thinking with reaction equation, was related to intermolecular interactions when the materiality of the external representations reconfigured, and the cartoon diagram was introduced. The new intra-activity with the materiality of the cartoon diagram reconfigured the meaning of product to articulate the feature of intermolecular interactions. The product of the hydrolysis took on the meaning as consequences of intermolecular interactions that facilitated the hydrolysis reaction, and intermolecular forces took on the meaning as interactions between the substrate and the G protein.

The analysis presented in this chapter illustrated the reconfiguration of the material-discursive-semiotic assemblage that differently enacted matter and meaning. When Mary was thinking with the reaction equation, the meaning of G protein's function was enacted in relation to having the right amino acid for stabilization of the transition state. When the cartoon diagram was introduced, the meaning of G protein's function was reconfigured to binding with GAP to get close to the substrate and stabilize the transitions state. When the AR model was introduced, the meaning of G protein's function was reconfigured again to utilizing the positive charge on the magnesium ion to stabilize the transition state. The materiality of the external representation, the signifying practices, and the semiotic features were entangled in the enactment of the meaning of G protein's function.

Chapter 9: Discussion

The issue of learning can be traced back to Socrates when he famously claimed that we cannot acquire new knowledge by learning, i.e., the learning paradox. Plato stated the paradox as following:

> Meno: And how will you inquire, Socrates, into that which you know not? What will you put forth as the subject of inquiry? And if you find what you want, how will you ever know that this is what you did not know?
> Socrates: I know, Meno, what you mean; but just see what a tiresome dispute you are introducing. You argue that a man can not inquire either about that which he knows, or about that which he does not know; for he knows, and therefore has no need to inquire about that—nor about that which he does not know; for he does not know that about which he is to inquire.
>
> --- The Essential Plato, Benjamin Jowett, p. 21

If we see the boundary between the known and the unknown as a sharp boundary, then learning seem impossible. As Socrates has argued, it appears that either one knows a priori what it is that one is looking for and therefore there is no need to learn, or one does not know what one is looking for and therefore one cannot expect to learn anything. If it is not possible to acquire any new knowledge that one does not already possess, then we either learn what we always already knew, or we are always ignorant because it would be impossible to recognize new knowledge even as we are trying to learn something new. In this dissertation, I set out to consider the issue of learning from a post-humanist performative perspective and experimented theoretically and methodologically with qualitative interview data from semi-structured interviews where undergraduate chemistry students were thinking with different external representations.

Barad's agential realism theorizes the production of scientific knowledge as involving matter as an active participant rather than passive object. For example, Barad argued that the material configuration for measuring position and momentum are mutually exclusive. The concepts of position and momentum are not ideational in nature but are material configurations and enactments. The indeterminacy of position and momentum of quantum particles is attributed to the impossibility of performing two mutually exclusive material intra-action. Theorizing scientific concepts as material enactments also implies that these concepts do not only exist in the mind of humans but are enacted with human and nonhuman participants. For example, Barad argued that the concept of momentum is enacted through the material of the entire physical configuration for the measurement of momentum within which the researcher is a part. This idea of material agency and concepts as performed offers a performative epistemology along with a relational ontology as alternatives to the worldview of representationalism, metaphysical individualism, and humanism.

Barad’s work focused on theorizing material’s participation in the enactment of scientific knowledge, but their ideas are also helpful for thinking about science learning. In the past, science education scholars have engaged with Barad’s ideas in the context of ecological education, but engagement in chemistry education remained rare. As a theoretical and methodological experimentation, this project developed agential variation theory to theorize learning as the boundary reconfiguration of material-discursive-semiotic assemblages that enact meaning differently. Within the context of learning with external representations, agential variation theory offered a perspective of viewing the meaning of external representations not as a link between a fixed signifier object and a fixed signified concept, but as an enactment through semiotic features, signifying practices, and participation from the materiality of the external representation.

Thinking about the learning with external representations of G-protein with the relational onto-epistemology of Karen Barad led me to attend especially to the material aspect of learning. G-proteins are part of our bodies, so when a learner was interacting with external representations of G-protein to understand the structure and function of G-proteins, an entity that contains the material of G-protein was relying on an object that does not contain any G-protein to understand a part of themself. Both the meaning of the external representation and the meaning of part of the learner became articulated through the intra-action between learner and external representation.

SF and Line of Flight

When considering the enactment and reconfiguration of meaning and knowledge in learning, it can be useful to consider Deleuze and Guattari's (1988) notion of deterritorialization and reterritorialization in a post-human sense. In the development of the constructs of deterritorialization and reterritorialization, Deleuze and Guattari focused primarily on the transformation of culture. Deterritorialization is the process by which a social relation, i.e., a territory, has its current organization and context altered, and reterritorialization is the process by which a new social relation is constituted through the alteration. Deleuze and Guattari (1988) noted that deterritorialization and reterritorialization occur simultaneously and used the term "line of flight" to describe the movement by which one leaves a territory and simultaneously extends the territory. For example, political propaganda can be seen as an attempt to reconfigure political culture by influencing people's ideas through information distributed on a large scale. Through political propaganda, people's existing political beliefs are altered (i.e., deterritorialization) to constitute new beliefs (i.e., reterritorialization).

Thinking with Barad's post-humanist perspective, the boundary between human and non-human is blurred, and social relations include relationships among both humans and non-humans. The work of deterritorialization and reterritorialization is not carried out by only humans but by assemblage of human and non-human actors. In the context of learning from external representation, deterritorialization and reterritorialization are useful constructs to think with the processes by which relationships among learner, external representation, and meaning are reconfigured to constitute new meanings and beliefs. Thinking variation theory with agential realism and line of flight, the object of learning that is differently discerned can instead be thought of the territory of learning that is differently deterritorialized and reterritorialized as the relations that constitute the territory of learning reconfigure.

Although SFs of each student's meaning making may resemble concept maps, there are important theoretical distinctions that must be considered when interpreting the two different types of figures. The use of concept maps is often associated with research on the associative structure of student conceptions from a cognitive perspective. The concept maps are seen as a representation of the knowledge structure of the learner. SF, however, cannot be attributed solely to the learner. SFs are maps of meaning weaved together by the assemblage of human and nonhuman that constitute the research space to temporarily hold meaning still. They can be thought of as tracing the lines of flight.

Tracing Interview Events

As researcher and author, in this dissertation, I do not speak from a "critical expert" or even a "critical friend" perspective, but compost (Haraway, 2016), producing ideas I had not thought of before and adding affirmatively to what is always already there because ideas are always already entangled with past, present, and future ideas. Interview participants have incorporated a variety of features of G protein function when thinking with different external representations. I used the term "thinking with" rather than "thinking about" to avoid invoking the idea that meaning of external representations was encoded within them while also acknowledging their work as referent for concepts. The meaning of G protein function as experienced by interview participants was enacted through the articulation of these features by their intra-activity. Some features were introduced in the student's proposed modes for G protein function when they are thinking with a particular representation, while other features were repeated as students move to the different representations.

Development of Agential Variation Theory

Rethinking the binaries of nature vs culture and human vs non-human helps to understand that not only humans "construct" knowledge but also that learning is a coproduction of several material-discursive-semiotic assemblages and thus a posthuman process. Learning is neither imposed upon humans nor does it happen on a human's own terms. Rather, learning happens within the material-discursive-semiotic environment in the form of "becoming with" humans, things, technologies, knowledge, etc. In turn, human-thing-technology-knowledge assemblages produce specific kinds of learning processes. Since the post-humanist perspective questions what a human body comprises, behaviors, attitudes, values, emotions, and cognition are not preexisting kinds of representation but rather dynamic co-formations of meanings and kinds of materiality, which emerges in material-discursive-semiotic practices.

Variation theory attempts to articulate the connection between that which is seen to be material and that which is seen to be psychological (in a sense, variation theory is a material-psychological perspective of learning). Vygotsky's sociocultural theory attempts to articulate the connection between that which is seen to be social and that which is seen to be psychological. The "cultural" is based on a distinction between scientific and everyday concepts, and the sociocultural perspective argues that a mature conceptual understanding is achieved when the scientific and everyday versions have merged. Agential realism attempts to articulate the connection between that which is seen to be material and that which is seen to be social. Synthesizing insights from all three schools of thought can produce a sophisticated analysis of the process of learning where connections between the material, social, and psychological are explored.

One key idea about Vygotsky's sociocultural theory is that two individuals who have similar levels of performance individually may have different levels of performance in collaboration with others. The difference in collaborative performance can be attributed to difference in individual abilities that cannot be measured with independent tasks. With agential realism as the onto-epistemological underpinning, the difference between independent performance and collaborative performance can be seen as two different configurations of intra-actions that enacted different boundaries between the subject and the object. The "cultural" in Vygotsky's sociocultural theory posits a distinction between scientific and everyday concepts.

New materialism such as agential realism illustrated that the boundary between nature (e.g., the human body and the material environment) and culture (e.g., meanings, norms, and values) is in fact not as clear as assumed traditionally. The natural does not pre-exist the sociocultural, and vice versa. From this perspective, the practice of science does not uncover facts about a pre-existing nature, nor does the practice of science incorporate (assimilate) empirical observations to pre-existing conceptual frameworks. In the agential variation theory account, external representation is a phenomenon where software, hardware, protein models, learner, developer, instructor, researcher, etc., become differentially intelligible to each other through intra-activities where representational, pedagogical, scientific, and technological practices come together. Investigating representational practices as part of this phenomenon requires tracing the patterns of how different practices constitute each other and reconfigure the boundaries of different entities.

External Representation, Language, and Meaning

The importance of the meaning-making processes begins from the standpoint that all meaning is made by specific human social practices (Lemke, 1988). When we say that the mastery of chemistry content knowledge means being able to talk/write chemistry like a chemist, we are talking about making the meanings of chemistry using the resources of spoken and written language. Talking and writing chemistry are social practices. They are parts of larger social activities (other parts may include conducting chemistry experiments, troubleshooting chemistry apparatuses, etc.). They are learned socially, function socially, and are socially meaningful (with the agential realism account, they are also learned materially, function materially, and are materially meaningful). Spoken and written language are social resources for making social meaning, and the specific semantic patterns of chemistry are institutionalized social formations, patterns of language use, and patterns of deployment of the social resources of language in chemistry communities.

Much of research on student learning science concerns the question of “who is using what kinds of language to describe scientific concepts and phenomena?” This question can be answered by presenting the research participants with an assessment instrument such as a concept inventory survey and measure their response. In this approach, language is presented as texts that represent particular relationships in the researcher’s hypotheses. Researcher participants will then become categorized as who they are (e.g., novice or expert) based on the ways in which they interact with the presented language. The question can also be answered by asking research participants open-ended questions in surveys or interviews, and recording the language used by research participants.

Questions about what is “naive” and what is “advanced” superimposed on some unitary one-dimensional scale serve to distract attention from the differences in modes of reasoning that may arise in particular situations. Such an unitary one-dimensional scale positions cultural development, both individually and socially, as a linear progression towards western modern science as supreme. However, challenging the unitary one-dimensional scale does not mean a commitment to the underlying relativistic notion that we should not make value judgements concerning whose cognition is "better" or more "advanced" — that all kinds of thinking and practice are equally valuable. While this stance may be a comfortable basis for academic discourse, it ignores the reality that in all domains of societal practice, particularly in education, those very value judgements and decisions have to be made every day (Engestrom, 1990). Therefore, the goal is not to opt out of value judgement, but rather to consider the possible implications of making value judgements and create space for exploring possible responses to these judgements.

In Chapter 3, I used the example of a flower and a computer to discuss the relationship between matter and meaning. Meaning of concepts cannot be reduced to physical objects, nor can they be reduced to merely symbols that are stored in memory. Thinking of the learning with external representations of G-protein with the relational onto-epistemology of Karen Barad led me to attend especially to the material aspect of learning. G-proteins are part of our bodies, so when a learner is interacting with external representations of g-protein to understand the structure and function of G-proteins, an entity that contains the material of G-protein is relying on an object that does not contain any G-protein to understand a part of themself. Both the meaning of the external representation and the meaning of part of the learner become articulated through the intra-action between learner and external representation. Further, the boundary between the external representation and the learner is enacted through this process.

Expanding Perspective on Qualitative Chemistry Education Research

With insights from Barad and Deleuze, a new qualitative research space can be explored from a relational onto-epistemological standpoint. Methodologically, critically reflecting on the epistemological standpoint and diffractively engaging with other standpoints can be a reflexive approach to establish rigor for qualitative research. This philosophical and methodological experimentation is of great practical concern. I believe that it is of importance not only to students and teachers of chemistry, and not just as a theoretical issue, but that it has implications for the activities of the scientific community and for the relation between this community and the "rest of society". It concerns the very practical questions of what we are doing when we are teaching and learning chemistry. How are we, as a scientific community, advancing knowledge that is relevant to the particular history of our field and the particular problems and conditions of society more generally. The thoughts we use to think other thoughts, the very ways in which we attempt to advance our knowledge, may enact a implicit limitation of what knowledge can be.

Recognizing the entanglement of ontology and epistemology entails that productions of knowledge are also productions of reality, in the sense that knowledge production will always have material consequences (Taguchi, 2012). In becoming with data, what is disclosed or produced is an event where it is possible to become-with the interviewee as they take part in a journey of intra-activities, where all the performative agents become differentially articulated and intelligible in relation to themselves as the event unfold. This journey emerges in the material-discursive intra-activities in-between the interviewee's hands, the protein diagrams, the QR code, the iPad, the AR mobile application, the interviewee's imagination of a protein, and the ideas they voice. The events are unfolded as a reality of creative imagination and post-human collaboration. In this reality, the interviewee is no longer a student who possesses or lacks various representational skills or competencies, but part of an assemblage where many performative agents collaborate in their mutual articulation. Reading from the data another possible material-discursive reality implies acknowledging our interdependence and co-existence with other bodies in the world (indeed, as Haraway has pointed out, we were never fully human) and constitutes a resistance against normative, anthropocentric points of view. What is produced is thus a material-discursive reality where that which has been considered passive is now seen as active in its intra-activities.

Like the classroom space positions instructors as insiders and students as outsiders-within, the interview space also positions the interviewer as the insider and the interviewee as the outsider-within. The interviewer often has the privileged view of the interview protocol and the meaning of the responses. Adopting a standpoint epistemology means that the perspectives of those who are positioned as outsiders-within are privileged as these individuals are placed in a unique position to point to patterns of meaning that those immersed in the dominant culture are unable to recognize. In the context of chemistry education research, these perspectives are often seen as lacking and need to be either changed or replaced by the perspectives of insiders.

When students are revising their model of how protein works with different types of external representation, one main change is the further articulation of their existing model. This phenomenon can be seen with a cognitive perspective as the learner discerning more critical features of the learning object, thereby developing a more sophisticated mental model, or be seen as new cultural artifacts become instrumentalized into learning tools to mediate the formation of a mental model about G protein. This can also be seen as the materiality and meaning of the protein-learner assemblage is reconfiguring and the boundary between matter and meaning of protein and learner are reconfiguring to give rise to different critical features and different mediation activities. The three sets of analysis are entangled with each other. Semiotic features are the aspects of the cultural artifact that become instrumentalized. The mediation of meaning by these semiotic features is the intra-action that produce bounded meaning and objects.

Future Work and Remaining Questions

Since this project is a theoretical exploration into chemistry education research on student learning with external representations from a relational ontological standpoint, there are still theoretical questions to be addressed. The theorization of learning as boundary reconfiguration may inform the qualitative description of learning, but it is unclear how this theorization can inform the measurement of learning gains or the effectiveness of pedagogy. If learning is the reconfiguration of temporary bodily boundaries, then how can instructors measure this reconfiguration and connect it to pedagogy? What is the pedagogical recommendation?

Future theoretical and methodological experimentation can further the engagement with agential variation theory in research on pedagogy in addition to research on learning. Students might not produce the behavior intended by pedagogy, but does that mean learning did not happen at all? If we see learning as a constant process of reconfiguration, the role of pedagogy can be viewed as reconfiguring the possibility of learning. Future research can explore the probabilistic view of the relationship between learning and pedagogy.

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