Designing Science Learning Environments That Support Emerging Bilingual Students to Problematize Electrical Phenomena

Enrique Alberto Suárez
University of Colorado at Boulder, enrique.suarez@colorado.edu

Follow this and additional works at: https://scholar.colorado.edu/educ_gradetds

Part of the Science and Mathematics Education Commons

Recommended Citation
Suárez, Enrique Alberto, "Designing Science Learning Environments That Support Emerging Bilingual Students to Problematize Electrical Phenomena" (2017). School of Education Graduate Theses & Dissertations. 98.
https://scholar.colorado.edu/educ_gradetds/98
DESIGNING SCIENCE LEARNING ENVIRONMENTS THAT SUPPORT EMERGING BILINGUAL STUDENTS TO PROBLEMATIZE ELECTRICAL PHENOMENA

by

ENRIQUE A. SUÁREZ

B.S., University of Oklahoma, 2007
M.S., Tufts University, 2012

A dissertation submitted to the
Faculty of the Graduate School of the
University of Colorado in partial fulfillment
of the requirement for the degree of
Doctor of Philosophy
School of Education
2017
This dissertation entitled:
Designing Science Learning Environments That Support Emerging Bilingual Students to 
Problematize Electrical Phenomena
written by Enrique A. Suárez
has been approved for the School of Education, University of Colorado Boulder

Dr. Valerie Otero, Chair

Dr. Noah Finkelstein

Dr. Kris Gutiérrez

Dr. Eve Manz

Dr. William Penuel

Date 08/24/2017

The final copy of this thesis has been examined by the signatories, and we 
Find that both the content and the form meet acceptable presentation standards 
Of scholarly work in the above mentioned discipline.

IRB protocol # 16-0081
Suárez, Enrique A. (Ph.D., Education, Curriculum & Instruction)

*Designing Science Learning Environments That Support Emerging Bilingual Students to Problematize Electrical Phenomena*

Dissertation directed by Professor Valerie Otero

**ABSTRACT**

This dissertation investigates how emerging bilingual students make sense of natural phenomena through engaging in certain epistemic practices of science, and the elements of the learning environment that created those opportunities. Specifically, the dissertation focuses on how emerging bilingual students problematized electrical phenomena, like electric flow and electrical resistance, and how the design features of the environment (e.g., sequencing of activities, linguistic practices) may have supported students as they made sense of phenomena. The first study describes how for students presented and evaluated mechanistic models of electric flow, focusing specifically on how students identified and negotiated a disagreement between their explanatory models. The results from this study highlight the complexity of students’ disagreements, not only because of the epistemological aspects related to presenting and evaluating knowledge, but also due to interpersonal dynamics and the discomfort associated with disagreeing with another person. The second study focuses on the design features of the learning environment that supported emerging bilingual students’ investigations of electrical phenomena. The findings from this study highlight how a carefully designed set of activities, with the appropriate material resources (e.g., experimental tools), could support students to problematize electrical resistance. The third study describes how emerging bilingual students engaged in translanguaging practices and the contextual features of the learning environment that created and hindered opportunities for translanguaging. The findings from this study identify and articulate how emerging bilingual students engaged in translanguaging practices when
problematizing electrical resistance, and strengthen the perspective that, in order to be equitable for emerging bilingual students, science learning environments need to act as translanguageing spaces. This dissertation makes three contributions to how science educators understand how elementary-aged emerging bilingual students learning science. First, I offer a detailed account of how emerging bilingual students engaged in epistemic practices to problematize electrical phenomena. Secondly, I argue learning environments need to create opportunities for emerging bilingual students to engage in productive epistemic work through leveraging multiple kinds of resources from their semiotic repertoires. Finally, this dissertation contributes to our understanding of how emerging bilingual students engage in translanguageing practices as they investigate and talk about the natural world.
DEDICATION

For Carl. I hope to instill as much inspiration and wonderment about the Universe in others as you did in me.
ACKNOWLEDGEMENTS

My outmost gratitude to my advisor, Dr. Valerie Otero. From the moment we met, Val has supported my research interests and passions, always ready to learn alongside me and guide my thinking. Additionally, I would like to thank Dr. Noah Finkelstein, Dr. Kris Gutiérrez, Dr. Eve Manz, and Dr. Bill Penuel, all of whom have mentored me and supported my work unreservedly. I have learnt so much from you, and I will be forever grateful for your care and your dedication.

Throughout my time in the program, I was also fortunate to count with the friendship and mentorship of Julie Andrew, Dr. Melissa Braaten, Dr. Erin Furtak, Dr. Ken Howe, Dr. Laurie Langdon, Dr. Daniel Liston, Dr. Enrique López, Dr. Liz Meyer, and Dr. Joe Polman. Thank you all for your support and encouragement. Thank you also to Sara MacDonald and Dr. Scarlett Ponton de Dutton, whose encouragement and support was invaluable.

I have been very lucky to count with great friends along the way who enriched my personal life and pushed my scholarly work: Jason Buell, Josie Chang-Order, Dr. David Hammer, Dr. Ian Her Many Horses, Dr. Lama Jaber, Dr. Christina Krist, Dr. Gina Quan, Dr. Deána Scipio, Becky Swanson, Dr. Michelle Wilkerson, and Dr. Kerri Wingert. Thank you for everything!

Thank you to my family, who have supported me unconditionally to pursue my dreams and taught me from a young age about the importance of service and justice. To my mom Elizabeth, my dad Enrique, my second mom Orietta, and three brothers – Alejandro, Bernardo, and Armando: no hay palabras que puedan expresar mi eterna gratitud y amor.

Finally, to the love of my life, Daisy Patton: I could not have done this without you. Thank you from the bottom of my heart for your love, your support, your friendship, successfully keeping me grounded, your kindness, and your humor (e.g., “How am I not myself? How am I not myself?”). You are my inspiration and role model. I am so proud of where we are headed.
CONTENTS

List of Tables.................................................................................................................................................. viii

List of Figures.................................................................................................................................................. ix

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

Chapter 2: Unpacking Disagreements Between Elementary-Aged Students About Their Mechanistic Models of Electric Flow.............................................................................................................. 6

Chapter 3: Supporting Elementary-Aged Students to Problematize Electrical Resistance................................................. 56

Chapter 4: Estoy Explorando Science: Translanguaging in an Out-Of-School Science Program for Emerging Bilingual Students.............................................................................................................. 107

Chapter 5: Conclusions and Implications......................................................................................................... 160

References.................................................................................................................................................... 172

Appendix....................................................................................................................................................... 180
LIST OF TABLES

Table 2.1: Linguistic features that index disagreements, adapted from Scott (2002, p. 306) ......................................................................................................................................................................................... 20

Table 2.2: Codes for identifying mechanistic elements (top), most frequently used linguistic markers of disagreement (bottom) ............................................................................................................................................................................... 25

Table 2.3: Classification based on explicitness and turn shape, from Pomerantz (1984) and Scott (2002) ......................................................................................................................................................................................... 26

Table 2.4: Summary of mechanistic models......................................................................................................................................................................................................................................................... 29

Table 3.1: Planned sequence of activities, and enacted sequence of activities.................. 73

Table 3.2: List of 5-min segments that contained talk about conceptual features of electrical resistance............................................................................................................................................................................................................................................... 80

Table 3.3: First- and second-cycle inductive codes related to conceptual features of electrical resistance ........................................................................................................................................................................................................................................ 81

Table 3.4: Explicit mentions of conceptual features of electrical resistance when using specific experimental tools........................................................................................................................................................................................................................................ 86

Table 3.5: Affordances and constraints of tasks and tools for problematizing electrical resistance ........................................................................................................................................................................................................................................ 103

Table 4.1: Dimensions of gestures as deductive codes for identifying and describing students’ gesturing........................................................................................................................................................................................................................................ 130

Table 4.2: Codes for distinguishing the collaborative goals achieved by students’ translanguaging........................................................................................................................................................................................................................................ 132

Table 4.3: Comparing number of exchanges in which students engaged in translanguaging practices through linguistic resources........................................................................................................................................................................................................................................ 132

Table 4.4: Comparing the meaning that can be derives from Grace’s statements without and with gestures........................................................................................................................................................................................................................................ 143

Table 4.5: Number of exchanges, per session, where Yesenia and Elio spontaneously transitioned between English and Spanish to address each other, classified according to the goals their translanguaging served........................................................................................................................................................................................................................................ 147
LIST OF FIGURES

Figure 2.1: Graphical representations of the groups’ mechanistic models, rendered by the researcher.................................................................................................................................................. 30

Figure 3.1: Conjecture Map (Sandoval, 2013) that guided the study’s design and retrospective analysis.......................................................................................................................................................... 69

Figure 3.2: Design of the template students used when drawing and investigating circuits of conductive ink............................................................................................................................................................................. 71

Figure 3.3: Explicit mentions of conceptual features of electrical resistance during each session. In Session 3 and Session 7, students began one investigation with one set of experimental tools and then switched to another investigation that involved using other tools........................................................................................................................................................................................................ 83

Figure 4.1: Times that Yesenia and Elio transitioned between English and Spanish, indexing translinguaging through linguistic resources........................................................................................................................................................................ 133

Figure 4.2: Main three dimensions of gesturing (deictic, iconic, and metaphoric) that students used when describing their observations and sharing their explanations about electrical phenomena........................................................................................................................................................................................................ 139

Figure 4.3: Yesenia traces the different wires as she describes how electricity moves through each circuit............................................................................................................................................................................. 144

Figure 4.4: Yesenia moves her right hand in a circle as she talks about why the lamp turns on............................................................................................................................................................................................................... 145

Figure 4.5: Number of exchanges with English-Spanish transitions in sessions where all four students were in attendance........................................................................................................................................................................................................ 149

Figure 4.6: Number of exchanges with English-Spanish transitions in sessions where only Yesenia and Elio were present........................................................................................................................................................................................................ 149

Figure 4.7: Mapping when the students and the instructor transitioned between English and Spanish during the last session of the program........................................................................................................................................................................................................ 151
CHAPTER 1

INTRODUCTION

Research in science education suggests that science learning is more effective when students engage in epistemic practices of the discipline (e.g., Ford, 2008; Ford & Forman, 2006; Lehrer & Schauble, 2006b; Manz, 2015), influencing current national educational policy (National Research Council, 2012) and standards, such as the Next Generation Science Standards (NGSS Lead States, 2013). For the purposes of this dissertation, I define epistemic practices of science as the cognitive and discursive activities learners engage in to co-construct knowledge about the natural world, such as planning investigations, and proposing and evaluating evidence-based explanatory models. However, students from underserved communities seldom learn science in environments where they get to engage in the epistemic practices of science (Bang, Warren, Rosebery, & Medin, 2012; Barton, 2001; Johnson, Brown, Carlone, & Cuevas, 2011). The emphasis on science practices requires that learning environments and educators actively support students from underserved communities achieve science learning goals. The NRC’s “Framework for K-12 Science Education” (NRC, 2012) acknowledges that unless science “approaches to instruction can be made more inclusive and motivating” for students from underserved communities, current inequities in opportunities to learn fueled by “low learning expectations and biased stereotypical views” of will remain (2012, p. 277). These students can succeed in science learning environments that foster culturally sustaining pedagogies and leverage students’ conceptual, linguistic, and cultural resources (Ladson-Billings, 1995; Paris & Alim, 2014).

The population of students who speak languages other than English is rapidly increasing in the US, and will continue to do so (Humes, Jones, & Ramírez, 2011). Either recent immigrants or born into multilingual families, the students represent a great variety of countries, languages,
and cultural practices, making them an incredibly heterogeneous group. These students are often placed in classrooms where teachers do not have the necessary training for supporting their learning, or school-specific resources to address their needs (Kindler, 2002). Schools with large numbers of students from underserved communities often relegate science classroom time over other tested subjects (Rivera Maulucci, 2010). This issue deepens in schools with large populations of students who speak English as a second language, often focusing their efforts on developing these students’ language fluency, literacy, and arithmetic skills (McMurrey, 2008). Guided by pressures to improve these students’ test scores and English fluency, these schools decide to neglect science classroom time, and even when it is taught the emphasis is often on students acquiring scientific vocabulary. This means that elementary-aged emerging bilingual students are not receiving adequate instruction in non-tested subjects, such as social studies and science (Slavin & Cheung, 2005). It is no wonder that students from underserved communities, such as emerging bilingual students, continue to lag behind their majority counterparts on opportunities to learn science (Duschl, Schweingruber, Shouse, 2007). These inequities raise the need to design science learning environments where emerging bilingual students have opportunities to learn about the natural world through engaging in epistemic practices.

Most of what we know about supporting elementary-aged emerging bilingual students to learn comes from research in language acquisition and bilingualism. These areas of research have yielded great insight into how to support students’ language development, but have not addressed how we can support these students to learn science by engaging in epistemic practices. Some science education researchers have focused their work on developing this area of inquiry. Specifically, researchers have proposed that emerging bilingual students come to the classroom with valuable conceptual, linguistic, and cultural resources for making sense of complex natural
phenomena (Ballenger, 2004; Rosebery, Ogonowski, DiSchino, & Warren, 2010; Rosebery, Warren, & Conant, 1992; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001). This research frames these students’ knowledge and ways of talking as productive building blocks for making sense of the natural world, rather than as obstacles. Moreover, this line of research proposes that science instruction should provide learning opportunities and supports for emerging bilingual students to co-construct knowledge about the natural world, rather than positioning them as consumers of knowledge and in need of remediation.

My dissertation research investigates how emerging bilingual students make sense of natural phenomena through engaging in certain epistemic practices of science, and the elements of the learning environment that created those opportunities. Specifically, the dissertation focuses on how emerging bilingual students problematized electrical phenomena, like electric flow and electrical resistance, and understanding the design features of the environment (e.g., sequencing of activities, linguistic practices) that supported four students as they engaged in epistemic practices. Here it is important to, once again, acknowledge how the linguistic and cultural heterogeneity of emerging bilingual student can present significant challenges for designing science learning environments that are equitable for all students. Therefore, the results from this dissertation should be considered in relation to the local context where it took place.

The first study focuses on how participating emerging bilingual students presented and evaluated mechanistic models of electric flow, focusing specifically on how students identified and negotiated a disagreement between their explanatory models. Drawing from research literature on disagreements (M. H. Goodwin, 1990; Pomerantz, 1984; Scott, 2002), I use a Discourse Analysis approach to examine students’ explanatory models, the linguistic features they used to express their opposition, and the explicitness and intensity of those disagreements.
The analysis shows that students proposed and evaluated mechanistic explanations (Russ, Scherr, Hammer, & Mikeska, 2008) about how electricity flowed through a circuit, disagreeing specifically about the direction of flow and what pushed the electricity forward. This disagreement was predominantly enacted through linguistic features that lessened the explicitness of the opposition, such as asking negative questions, which in turn served to diminish or avoid future conflicts. The results from this study highlight the complexity of students’ disagreements, not only because of the epistemological aspects related to presenting and evaluating knowledge, but also due to interpersonal dynamics and the discomfort associated with disagreeing with another person.

The second study focuses on the design features of the learning environment that supported emerging bilingual students’ investigations of electrical phenomena. Specifically, this study examines how a sequence of investigations and associated experimental tools supported students to problematize electrical resistance. I analyzed portions of the video through coding students’ explicit talk about aspects of electrical resistance (e.g., material composition, length, or width of a resistor), which led to two main findings. The first finding suggests that the designed tasks and the experimental tools created opportunities for students to problematize multiple aspects of electrical resistance. The second findings from this study suggests that each distinct set of experimental tools introduced affordances and constraints for supporting students to problematize electrical resistance. Combined, these findings highlight how a carefully designed set of activities, with the appropriate material resources (e.g., experimental tools), could support students to problematize complex natural phenomena, such as electrical resistance.

The third study describes how emerging bilingual students engaged in translanguaging practices (García & Kleyn, 2016; Otheguy, García, & Reid, 2015) and the contextual features of
the learning environment that created and hindered opportunities for translanguaging. For this study, I coded all the exchanges in which students transitioned between named languages (e.g., Spanish and English) and/or used gestures, described how these translanguaging practices served different collaborative functions, and detailed possible instructor moves that might have supported students’ translanguaging. The first finding shows that participating students engaged in translanguaging practices throughout the program, leveraging both gesturing and different named languages. The second finding suggests that not all students had opportunities to engage in translanguaging, and when they did their translanguaging served different purposes. The third finding describes how the instructor set the linguistic expectations of the learning environment, creating translanguaging opportunities for some students, and closing opportunities for others. Combined, these results identify and articulate how emerging bilingual students engage in translanguaging practices when problematizing natural phenomena, and strengthen the perspective that, in order to be equitable for emerging bilingual students, science learning environments need to act as translanguaging spaces (Wei, 2011).

Together, these manuscripts describe the design features of a science learning environment that created opportunities for emerging bilingual students to problematize complex electrical phenomenon. These students asked important questions about the phenomena they observed, had the authority to plan and implement investigations for addressing those questions, and co-constructed evidence-based explanations of their observations in a community of learners. Through the analysis presented here, my goal is to exemplify how the design features of the learning environment created opportunities for students to engage in science disciplinary practices in order to problematize the natural world, opportunities that seldom are available for students, especially those from underserved communities.
CHAPTER 2

UNPACKING DISAGREEMENTS BETWEEN ELEMENTARY-AGED STUDENTS
ABOUT THEIR MECHANISTIC MODELS OF ELECTRIC FLOW

By:

Enrique Suárez

To be submitted to: Science Education
Paper 1: part of a thesis submitted to the School of Education
INTRODUCTION & RATIONALE

Reforms in science education have always called for students to be more actively involved in the process of constructing scientific knowledge. Research suggests that science learning is more effective when students engage in disciplinary practices to co-construct and evaluate knowledge about the natural world (e.g., Ford, 2008; Ford & Forman, 2006; Lehrer & Schauble, 2006b; Manz, 2015). Current national standards (National Research Council, 2012) have codified the goal that students learn science through participating in disciplinary practices, some of which promote students engaging in discussions through talk or writing to create explanations for the phenomena they observe. Acknowledging the importance of students interacting with each other when co-constructing knowledge, science learning environments should offer opportunities for students to engage in discourse that leads to robust and meaningful conceptual understanding (Michaels, O’Connor, Hall, & Resnick, 2010; Michaels, O’Connor, & Resnick, 2008). Specifically, the goal is for students to engage with their peers’ ideas through proposing and evaluating ideas, building an argument for or against an idea, and convincing each other of the accuracy of their explanations (Duschl & Osborne, 2002; Ford & Forman, 2006; Michaels, Shouse, & Schweingruber, 2007).

Engaging in argumentation asks that students identify, navigate, and resolve differences between their ideas, and move towards consensus on more productive mechanistic explanations. Thus, disagreements are crucial to the literature on scientific argumentation, because of the opportunities created for students to refine their models. For some researchers (e.g., Erduran, Simon, & Osborne, 2004; J. Osborne, Erduran, & Simon, 2004), the quality of students’ arguments is paramount, and is determined by how they measure up against others’ explanations. Based on the application of Toulmin’s Argument Pattern (TAP; Toulmin, 2003), arguments that include rebuttals, oppositions, and/or disagreements are considered more conceptually
productive than those that just stating evidence-based claims. Other researches are more concerned with students engaging in academically productive talk (e.g., Michaels et al., 2008, 2007), disagreements are at the core of dialogical rationality, “through which participants advance arguments and counterarguments” (Michaels et al., 2008, p. 284). From this perspective, disagreements are a tool for holding students accountable not only to the learning community, by attending to each other’s ideas, but also accountable to the community’s standards of reasoning.

Whether focused on the quality of an argument or academically productive talk, science education has often prized discussions where students outwardly disagree with each other. Expecting and valuing explicit disagreements between students can be problematic for two reasons. First, promoting explicit disagreements between students can be limiting to their participation and learning, given that publicly expressing opposition with a peer’s statement can be challenging and often dispreferred (Pomerantz, 1984). Secondly, students can resort to a host of linguistic markers to covertly negotiate differences of ideas that may not be perceived as confrontational (M. H. Goodwin, 1990; Pomerantz, 1984; Scott, 2002), which would be missed by analytical and pedagogical approaches that focus on explicit disagreements. I argue, then, that it is key to understand the epistemological and interpersonal dynamics of how students negotiate differences in their ideas about the natural world. This study investigates the complex discursive and epistemic work elementary-aged students did when sharing, evaluating, and disagreeing about mechanistic models of electric flow. Specifically, I describe the content and structure of the disagreement, and identify the linguistic markers students used for foregrounding the differences between their models and, yet, mitigating the any potential overt confrontation.

The manuscript is structured as follows. I first present a brief review of the literature on argumentation in science learning, focusing on how differences between students’ ideas are
identified and valued. This section is followed by a review of the literature on disagreements between children and between adults, attending to the structures (i.e., parts and sequencing) of disagreements, their explicit or implicit nature, and the linguistic features that index opposition. I then outline the study’s context and the characteristics of the dataset from which I drew the case analyzed here, and the strategies I used for analyzing the disagreement between students’ models of electric flow. Next, I present the results of my analysis on how students negotiated the differences between their mechanistic models, focusing on how the disagreement was foregrounded, yet mitigated. The manuscript ends with theoretical and pedagogical implications for identifying different forms of disagreements when discussing science models.

**LITERATURE REVIEW**

*Science as Argument: Proposing and Evaluating Mechanistic Models*

The primary goal of scientific investigations is to understand natural phenomena through constructing and refining explanatory models (Driver, Newton, & Osborne, 2000; Fleck, 2012; Lehrer & Schauble, 2006a). These explanatory models are built on evidence and reasoning that can connect the evidence to the claim, and can convince peers (K. L. McNeill & Krajcik, 2008). From this perspective, it is important to consider the process of constructing scientific knowledge as a social process, in which many individuals produce and critique knowledge with the sole purpose of refining the community’s understanding of natural phenomena (Ford, 2008; Ford & Forman, 2006). Many argue that models allow scientists to externalize their explanations and predictions, and engage in discussions about the power of those ideas in explaining their observations of the natural world (e.g., Louca & Zacharia, 2012; Manz, 2012). Therefore, constructing and refining models is a key disciplinary practice that supports conceptual understanding.
Scientists rely on multiple kinds of explanatory models for making sense of and predicting observations, like mathematical and probabilistic models. One specific type, mechanistic models, has been foundational for advances in scientific knowledge because of their detailed descriptions of how the interactions between a number of parts within complex systems produce the behaviors that underlie the phenomena we observe (Glennan, 2002). MacHamer and his collaborators (MDC, 2000) define mechanisms as “entities and activities organized such that they are productive of regular changes from start or set-up to finish or termination conditions” (2000, p. 3). In this definition, entities are the “things” (e.g., fundamental particles, atoms) involved in the phenomena; and activities are the actions and interactions between entities that produce the outcome. Using electricity as an example, entities can be electrons that engage in different types of activities, like moving freely around the conductor and colliding with other particles in the conductor. Setup conditions account for the entities present and describe the ways in which the structure of the physical and temporal context will determine how these entities engage in activities. For example, before electricity begins to flow through a conductor, electrons must be free to move, a push source is necessary, and the circuit must be closed. Finally, termination conditions describe the system’s final state, and what it is that entities are doing without producing any more changes. For example, once a lamp in a circuit is lit, the conductor has reached an ideal state of equilibrium, in which moving electrons transfer their energy to each other through constant collisions. While most mechanistic models involve nanoscopic entities (e.g., electrons), these kinds of models could address macroscopic entities (e.g., stars), too. From this point forward, when I say explanations, I am referring to mechanistic explanations.

If our goal is for students to engage in disciplinary practices of science, creating opportunities for formulating and presenting mechanistic models should also be a priority, often
lost in traditional science instruction (K. L. McNeill, Lizotte, Krajcik, & Marx, 2006). Through engaging in constructing explanations, students can deepen their conceptual understanding and even be motivated to continue pursuing investigations for making sense of the natural world (Driver et al., 2000; L. Kuhn & Reiser, 2005; J. Osborne et al., 2004). However, most modeling that happens in classrooms tends to be causal in nature, failing to address the often multiple and complex processes that give rise to the phenomena students observe. Russ and her collaborators (Russ et al., 2008) argue that, while causality is productive for understanding the natural world, it is not sufficient for explaining the detailed processes of how phenomena arise, i.e., mechanisms. Based on this reasoning, the ultimate goal should be for students to engage in model-based reasoning, in which they identify key players, their properties, and how they interact with each other to construct a model that accounts for and represented important relationships (Lehrer & Schauble, 2006a; Louca & Zacharia, 2012; Windschitl, 2004). Constructing mechanistic models can support students’ learning through creating opportunities for them to identify and leverage their ideas and reasoning in the service of making sense of the natural world. Additionally, emphasizing mechanistic and model-based reasoning in science learning environments highlights the need for educators to assess how students develop and engage in disciplinary practices to make sense of the natural world, rather than the correctness of their explanations.

**Disagreeing about models in science learning environments**

A crucial step in coming to consensus is for students to evaluate and refine the mechanistic models that have been presented, with the intent of advancing the community’s understanding (Ford, 2008; Ford & Forman, 2006). And while there is agreement that students should convince each other that their ideas have the most explanatory power and engage in persuasive consensus-building (e.g., Duschl & Osborne, 2002; L. Kuhn & Reiser, 2005; Michaels et al., 2007), there are different perspectives on what this process entails. Part of students persuading their peers is
identifying differences in explanations and, hopefully, reconciling discrepancies based on evidence from the investigations. The presence of a disagreement can create the opportunity for students to engage in dialogic discourse about their ideas, providing a foundation for furthering their conceptual understanding. And while much has been written about dialogic discourse in science learning environments, the multiple forms for disagreements remain somewhat underspecified. Therefore, it is important to further characterize how to identify and investigate disagreements between students about their mechanistic models of the natural world.

One specific line of research useful for understanding disagreements between students when presenting and evaluating mechanistic models focuses on analyzing students’ arguments according to Toulmin’s Argument Pattern (TAP; Toulmin, 2003). Researchers from this perspective (e.g., J. Osborne et al., 2004) propose that engaging in dialogic discourse supports students to coordinate evidence from investigations with previous experiences and scientific knowledge to construct explanations. For these researchers, an argument is a discursive sequence whose quality is determined by the presence of certain features from TAP (e.g., claims, rebuttals and disagreements) in the students’ arguments and/or counter-arguments.

Based on this model, these researchers propose a four-level heuristic for assessing the quality of students’ contribution to the discourse, with the intention of encouraging students to eventually reach the highest level of quality (J. Osborne et al., 2004). Specifically, the explicit presence of rebuttals and challenges are taken as markers of complex epistemic work, especially when compared to arguments that only propose claims and evidence (Erduran et al., 2004; J. Osborne et al., 2004). For example, the second highest level of argument (Level 4) must contain “a clearly identifiable rebuttal” (Erduran et al., 2004, p. 928) that relies on supporting data and related warrants. These clear rebuttals were identified during the analysis through focusing only
on exchanges “whereby students were clearly opposed to each other were traced” (J. Osborne et al., 2004, p. 1007). An example of a rebuttal would be a student claiming professional zoos would not hurt animals, while another student counters with, “But they might scare other animals by seeing some sedated animal being dragged off” (Erduran et al., 2004, p. 929); Erduran and her collaborators consider this to be a weak rebuttal and, therefore, a low-quality argument. Alternatively, an example of a high-quality argument would be when a student claimed that part of the moon gives out light and another student countered, “The moon doesn’t give out light … because the light that comes from the moon is actually from the sun” (Erduran et al., 2004, p. 930); in addition to the explicit opposition, this rebuttal included data to support the opposition.

While it is desirable for students to support their counter-arguments with data and warrants, focusing only on “clearly identifiable rebuttals” could be limiting for identifying and investigating disagreements. For one, researchers would count on a restricted tool set for identifying and understanding what disagreements between students about their ideas look like. Moreover, in its emphasis on teachers increasing the frequency and quality of their students’ arguments (i.e., arriving at Level 4 arguments), this framework could leave out other less obvious ways in which students can enact opposition towards each other’s explanatory models.

Another line of research useful for understanding how teachers can support students to engage in argumentation is “Accountable Talk” (Michaels & O’Connor, 2012; Michaels et al., 2008, 2007), which expects students to overtly state whether they agree or disagree with their peers’ ideas. These authors propose that discussions are central to students’ sense-making and conceptual understanding, as students state evidence-based claims and evaluate their peers’ explanations based on observations and reasoning. Students are expected to be accountable to: (1) the learning community, as they listen intently to their peers’ explanations and engage with
them; (2) the standards of reasoning, as students evaluate the logic and plausibility of conclusions; and (3) accountability to knowledge, committing to presenting only facts and the evidence to support their claims. Being accountable to both the learning community and the standards of reasoning creates a situation in which students are constantly listening to their peers’ ideas and assessing the explanatory power of the explanatory models.

As part of promoting accountable talk, teachers can rely on Talk Moves that encourage students to engage with their peers’ explanations (Michaels & O’Connor, 2012). Specifically, to support students to think with others, teachers can use a talk move that asks students to agree or disagree with their peers’ ideas and state the reasoning for their position (Talk Move 7; Michaels & O’Connor, 2012). When prompted like this, students are expected to explicitly state their position in relation to their peers’ ideas, and provide evidence-based supports or rebuttals. For example, when a third grader claimed 24 was an odd number “because three goes into it,” the teacher asked another student, “Miranda, do you agree or disagree with what Paulo said?”, to which Miranda replied, “Well, I sort of … like, I disagree?” (Michaels et al., 2008, p. 290). The goal is for students to eventually use the same talk moves to engage in academically productive talk with each other, being more comfortable to explicitly state whether they agree or disagree with their peers’ ideas, rather than waiting to be prompted but the teacher. While Talk Moves can be useful pedagogical strategies for teachers and can scaffold students to engage with each other’s ideas, this framework does not account for the possibility that interpersonal dynamics may steer students from explicitly disagreeing with each other. Expecting explicit statements of opposition may limit our understanding of students’ participation in discussions, as well as the pedagogical strategies that could support students to engage in productive epistemic work.
The research outlined here on disagreements has made significant contributions to teaching and learning science. However, it can be strengthened by including a more expansive set of analytical tools for understanding the vast diversity of epistemic and discursive practices that support students’ science learning, especially ones that include and value multiple forms of disagreements. For that, I build on research from Discourse Analysis and Conversation Analysis.

Functional, Structural, and Linguistic Features of Disagreements

In order to develop a more robust set of analytical tools for identifying and understanding disagreements between students, we can look at how other fields have described and investigated opposition between speakers. First, it is important to understand how the speech and discursive move between participants can orient towards disagreements, or not. This will be important for understanding the substance of disagreements, for example, how a person’s speech can try to avoid opposition from a co-participant (e.g., another student). Secondly, it will be important to identify the parts and sequencing (i.e., structure) of disagreements between speakers, such as when negotiating differences between mechanistic models. Understanding structure of a disagreement can be helpful for understanding the process through which ideas are presented, evaluated, and hopefully refined. Finally, it is important to understand how interlocutors’ linguistic choices (e.g., use of questions and/or negations) may indicate that an overt or implicit disagreement is taking place. To address all these theoretical and analytical concerns, I build on the work of Pomerantz (Pomerantz, 1984) on orienting talk toward agreements or disagreements, on M. Goodwin research on disagreements between children (M. H. Goodwin, 1990), and on Scott’s work on discursive markers of disagreement between adults (Scott, 2002).

Pomerantz’s work (1984) shows how discourse is structured to elicit certain responses from another speaker, preferring or dispreferring certain responses, like disagreements. Pomerantz suggested that participating in social situations often requires that people make assessments of
referents like observations or explanations, which are volunteered to other speakers and, often, solicit a response. By inviting a second assessment from a co-participant, the initial speaker is granting access to the referent in question and, therefore, creating opportunities for exchanges and communication. Specifically, Pomerantz posited that a person can make decisions on how to structure and offer an “initial assessment” (e.g., an opinion) in order to elicit one or multiple actions from the co-participant(s), inviting others into the conversation (Pomerantz, 1984, p. 63); much like a student asking a peer about their interpretation of an observation. Of all the possible actions that initial assessments can elicit, agreements and disagreements are some of the most relevant ones the recipients can initiate as their second assessment. However, the formulation of initial assessments can signal to the recipient that an agreement is preferred over the alternative.

Pomerantz distinguished between different types of initial assessments according to the “preferred” and “dispreferred” next action they invoke from the recipient. For example, a statement like, “it’s a beautiful day, no?” is structured to prefer for the co-participant to agree; statements like, “Did I ruin your weekend?” disprefer for the co-participant to agree, since doing so could be impolite. Thus, “preferred-action turn shapes” maximize the occurrences of desired actions (e.g., agreement) by initial assessments, while “dispreferred-action turn shapes” minimize the likelihood of certain actions (e.g., disagreement) (Pomerantz, 1984, p. 64). This distinction is important because it gives insight into how students can orient towards disagreements when engaging with each other’s ideas, or try to avoid them altogether.

Furthermore, Pomerantz (1984) described how her participants saw overt disagreements “as uncomfortable, unpleasant, difficult, risking threat, insult, or offense” (1984, p. 77) and avoided disagreeing when possible. In other words, disagreements were almost always avoided and/or the dispreferred next action. Through her ethnographic research, Pomerantz (1984) explored the
Comparing preferred and dispreferred action turn shapes in the context of how adults’ second assessments agreed or disagreed with the prior speaker, particularly in a social context in which agreement was preferred. However, even if the initial assessment preferred agreements as the next action, disagreements were sometimes inevitable. When this occurred, adults presented weak disagreements characterized by hesitant pauses, withholding second assessments, and even agreement components that were conjoined with disagreement components and followed by a contrast conjunction (e.g., “I see your point, except that it’s only part of the story”). Adults could also strongly disagree with their co-participants, although less often, through second assessments that contained contrasting evaluations and did not include any agreement components.

M. Goodwin’s ethnographic research described and analyzed the structure of the disagreements between the “Children of Maple Street” (1990), and associated discursive moves. Unlike Pomerantz’s participants, Goodwin observed that disagreements were an integral part of social meaning-making for these African-American children and, therefore, disagreements were often the preferred-action their turns oriented towards. Moreover, children’s disagreements presented recurring structural components and sequencing, regardless of the content of the disagreement: a beginning, extensions, and an end. Goodwin described multiple ways in which disagreements got underway, although predominantly they were started by the first expression of opposition, most often in the form of swiftly stated polarity expressions (i.e., yes/no) at the beginning of the turn. Secondly, children could repeat a portion of their co-participant’s talk with the intent of locating the “trouble source in another’s talk” (M. H. Goodwin, 1990, p. 146), often without allowing the initial speaker to repair the utterance for themselves. Finally, disagreements could begin when children identified the trouble source in their co-participant’s statement and substituted it for the correct utterance, again curtailing any possibilities of self-repair from the
speaker. Some of these starters of disagreements resemble how the science education literature has framed disagreements, particularly statements of polarity. However, it would be optimistic to expect that similar patterns in disagreements between children would spontaneously arise in the science classroom, not only because of how children are required to behave within schools, but also the different discipline-based discursive practices students are expected to engage in. Still, M. Goodwin’s work begins to elucidate other ways in which students in science learning environments could engage in disagreements beyond overt statements of opposition.

M. Goodwin also described notable discursive moves that could extend and/or conclude disagreements. Specifically, Goodwin observed that children would extend a dispute by “recycling” (1990, p. 158) their previous positions, deploying the same expressions of opposition described above: terms of polarity, repetitions and substitutions, and even questions that mitigated correcting and disagreeing with their co-participants. Justifications could also extend disagreements between children, rather than placating them, because “the focus of the dispute shifts to debate the new justification” (Goodwin, 1990, p. 163). Finally, Goodwin observed two ways in which disagreements ended. Most often, disagreements concluded without “any sharp indication that either position has ‘won’ or ‘lost’” (Goodwin, 1990, p. 157), like a child doing something to break up the argument and disrupting the sequencing of the disagreement. Alternatively, disagreements ended when one of the children would forgo their previous position and accept the correctness of their co-participant’s position; this often lead the child to revise their own position, although not necessarily. This perspective is particularly helpful for science education because it can give researchers and educators a sense of whether a student’s explanation convinced their peers, or if the disagreement would come to an end without a
definitive resolution. Goodwin’s work on how disagreements begin, get extended, and end, as well as the different linguistic makers used, lay the foundation for Scott’s research (2002).

Scott (2002) sought to systematize the process of identifying discursive features that index disagreements. Specifically, Scott’s goal was to “define the linguistic constitution of disagreements” (2002, p. 302), as well as describe how patterns of certain linguistic features give rise to different types of disagreements. Scott analyzed disagreements between adult political pundits during face-to-face discussions on a televised talk show that focused on controversial, current-events topics on a news network. Based on extant literature on disagreements (e.g., M. H. Goodwin, 1990), and quantitative and qualitative analyses of the show’s transcripts, Scott identified twelve distinct linguistic features speakers used when disagreeing with each other; for a complete list of the linguistic features, see Table 2.1. One of the features she identified in the speakers’ discourse when disagreeing with each other were words that indicated likelihood, possibilities, and/or obligations (i.e., modals). Scott also observed co-participants using questions to disagree with each other, especially those that included wh-type questions (e.g, what, when, why, who, how). Scott concluded that the presence of these linguistic features indicated disagreements between speakers. Based on her analysis, Scott constructed a continuum for describing the overt nature of disagreements, with foregrounded disagreements on one end, described as explicit and hostile, and included high frequencies and co-occurrences of the twelve linguistic features; and backgrounded disagreements on the other end, which were described as implicit and calmed, and included low incidences of markers of disagreements. Scott’s work continues to be regarded as a detailed list of linguistic features that index disagreement in English, and has been extended into other languages (e.g., Chinese, Farsi, Spanish).
As shown by this review of the disagreement literature, disagreements constitute a rich interactional and discursive tapestry that go beyond overt expressions of opposition (e.g., “I disagree with you”). Pomerantz observed how participants tended to shape their turns to disprefer disagreements, M. Goodwin’s work elucidated the structure followed disagreements between children and related discursive moves, and Scott’s research provided a broad list of linguistic features that point to the presence of disagreements. All three lines of research give
insight into the structure and elements of disagreements, constituting a potentially useful productive analytic toolkit. These tools can help science education researchers identify when and how students present and evaluate their reasoning, especially when using discursive practices that may not be currently recognized as constituting a disagreement. Moreover, understanding the various linguistic features students may use when disagreeing with each other can help educators recognize when differences are being negotiated, and employ pedagogical strategies that can support students to engage in argumentation, especially when students may be reluctant to explicitly express opposition. Building on this work can help science education researchers shed light onto the complex and nuanced ways with which students identify and negotiate differences between their mechanistic models of natural phenomena. This study, then, builds on these works on disagreements to better understand how elementary-aged students identify and resolve differences about their mechanistic models about electric flow through a circuit. Specifically, I address the following specific research questions:

1. What aspects of their mechanistic explanations students focus on when disagreeing with each other’s reasoning about electric flow?

2. What are the various discursive strategies and linguistic features students leverage when disagreeing with each other’s mechanistic models?

3. What aspects of students’ disagreements about the flow of electricity through a circuit are explicit, and which are implicit?
METHODOLOGY

Context and Participants

The data were collected in an out-of-school science program for elementary-aged emerging bilingual students\(^1\), centered on investigating and explaining electrical phenomena. The program met eight times throughout the summer (once per week) in a public library, each session lasting between 60 and 80 minutes. During each session, students worked in small groups to experiment with different kinds of circuitry materials, propose explanations for their observations, and participate in large-group discussions about their ideas. The program enrolled seven children, although attendance fluctuated and not all children were present during every session.

Only four of the students (two pairs of siblings) consented to participate in the research, and were present during the session I analyze below. These students were (pseudonyms): Yesenia, a Latina 4\(^{th}\) grader, and her brother Elio who was in 2\(^{nd}\)-grade; and Toben, a 4\(^{th}\)-grade Nigerian-Japanese student, and his sister Grace, who also was in 2\(^{nd}\) grade. While all four students were emerging bilingual students, English was common to all and became the program’s *lingua franca*; students still were encouraged to speak to each other in whichever language they felt comfortable in and thought was most useful. For most of the program, Yesenia and Elio worked together on their experiments and explanations, and Toben and Grace worked together, as well. Eventually students would tire of working with their siblings, and requested pairing off with another student, or do the investigations individually. The exchange I analyze in this study occurred during Session 4 of the program, when students built circuits with traditional tools (e.g., battery, wires, lamps) and explained how they thought electricity flowed through a circuit to light

\(^1\) These students are often referred to as English Language Learners (ELLs). In this paper, I build on the work of critical scholars (García, 2009b; Gutiérrez & Orellana, 2006) who propose the term “emerging bilingual students” to celebrate these students’ bilingualism, rather than privileging English above other languages, and highlight that they are learners of more than just English.
up a lamp; I had no requirements for what model of electric flow students proposed. This was Yesenia and Elio’s first time attending the program, while Toben and Grace had already built a successful circuit during the prior session and had begun proposing a model of electric flow.

**Data Collection**

Each session was recorded using both video and audio recorders, capturing students’ talk, the way they interacted with the investigation materials, and multimodal representations of their ideas. When students worked in small groups, a second camera was set up to capture how students worked through the investigation and discussed their thinking. In total, I recorded close to 12 hours of video and 10 hours of audio, from which I selected the episode I analyze in this study. Finally, I completed journal entries for each session that recorded relevant takeaways about learning and interactions (e.g., models proposed, discussion patterns).

**Data Selection and Data Analysis**

The selection process began with reducing the dataset (M. Miles, Huberman, & Saldaña, 2013) into manageable portions that could be conceptually interesting and, later, analyzed qualitatively. I began by reviewing the video recordings of each session, searching for instances in which students disagreed with each other either when working in pairs on their experimental investigations, or in the whole-group presentation of ideas. In order to identify episodes of disagreements, I build on Goodwin’s work (1990) and chose the unit of analysis to be oppositional sequences of three or more turns, bound by the first expression of opposition (see Table 2.1) and agreement and/or change in position. This study analyzes students’ participation over the course of one full unit of analysis, which began with the questioning of a student’s model, and ended with students agreeing on a common model. Over the nearly 12 hours of video recordings, I identified 26 episodes of disagreements between students.
After identifying instances of disagreements during the activities, the second step was to inductively determine the nature of the disagreement. Specifically, the content of the disagreements seemed to fall under three main categories: (i) disagreements about mechanistic explanations, in which students argued over the explanatory power of their ideas; (ii) disagreements about experimental set-ups, in which students argued over the logistics of conducting experiments; and (iii) disagreements about graphical representations of their ideas, in which students argued over the merits of different modalities for representing their thinking. While students disagreeing about implementing experiments and representing their thinking can be valuable for understanding opposition when learning science, these two categories did not include students presenting and evaluating mechanistic models, which is the study’s focus. Therefore, the analysis focuses on the first category of disagreements, which occurred when students presented and evaluated mechanistic models about electric flow.

This study analyzes one episode, in which students presented and evaluated each other’s mechanistic models; the only disagreement in the dataset with a clear beginning, extension, and ending. This eight-minute exchange happened during the program’s fourth session, when the four students mentioned above investigated how electricity flows through a circuit, as mentioned above. I transcribed this exchange in its entirety.

The first stage in the analytical process was to describe the mechanistic models that each group presented during the whole-group discussion, and identify the different elements. Specifically, I interpreted students’ models to understand the mechanistic processes they described, using Russ et al.’s (2008) elements of mechanistic reasoning to deductively identify elements of students’ explanatory model of electric flow (see Table 2.2, top). I relied on these

---

2 Transcription conventions: [] overlap; - self interruption; … pause; (   ) deictic terms; ((   )) gestures; :: extended speech; other punctuation added for increasing readability.
elements, especially the activities the entities were involved in, to compare the different students’ models and establish salient differences between them.

Table 2.2: Codes for identifying mechanistic elements (top), most frequently used linguistic markers of disagreement (bottom).

<table>
<thead>
<tr>
<th>Mechanistic Elements</th>
<th>Codes</th>
<th>Examples from the Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup conditions</td>
<td>“Without the battery or wires, none of the stuff would work”</td>
<td></td>
</tr>
<tr>
<td>Entities and their properties</td>
<td>“When the energy (entity) hits the wire, it goes through the wire, through the metal (activity)”</td>
<td></td>
</tr>
<tr>
<td>Activities</td>
<td>“We disconnected this wire and left it like that, the energy would freeze and it wouldn’t be able to run through”</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Linguistic Markers of Disagreement (frequent)</th>
<th>Codes</th>
<th>Examples from the Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Questions</td>
<td>“How would the circuit work?”</td>
<td></td>
</tr>
<tr>
<td>Modals</td>
<td>“The energy couldn’t go through”</td>
<td></td>
</tr>
<tr>
<td>Negation: Nonaffixal</td>
<td>“Why wouldn’t there be any energy?”</td>
<td></td>
</tr>
<tr>
<td>Discourse markers of negation</td>
<td>“But how does the energy cross the light bulb?”</td>
<td></td>
</tr>
</tbody>
</table>

The second analytical stage consisted of identifying the linguistic features present during the exchanges between students that indexed disagreements. My goal was to compile a broad set of codes that could give help me identify all the different ways in which students’ discourse could be enacting disagreements. To achieve that goal, I used the twelve linguistic features identified in Scott’s (2002) research, which overlapped with the markers of disagreement Goodwin (1990) described in her ethnographic work. I coded the transcribed discussions between students with these deductive codes, attending to how the disagreements students enacted related to the mechanistic models they presented and evaluated. Since I could not anticipate which linguistic features students would use when disagreeing with each other, I used all of the markers outlined in Table 2.1; some linguistic features were more common than others (see Table 2.2, bottom).

The last stage of analysis consisted of exploring the action that students’ exchanges oriented towards, as well as the explicitness of their disagreements. Specifically, building on Pomerantz’s (1984) distinction between preferred- and dispreferred-action turn shapes, and Scott’s (2002)
spectrum on explicitness, I developed a sorting matrix for categorizing students’ disagreements (see Table 2.3). This system for categorizing the function and explicitness of disagreements was helpful for giving nuance to the disagreement between students, by understanding the richness with which students could engage with and evaluate their peers’ ideas.

Table 2.3: Classification based on explicitness and turn shape, from Pomerantz (1984) and Scott (2002).

<table>
<thead>
<tr>
<th>Explicitness</th>
<th>Dispreferred-action: Mitigate Disagreement</th>
<th>Preferred-Action: Highlight Disagreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backgrounded: Implicit</td>
<td>“Would it freeze or turn back to the battery?”</td>
<td>“How does the energy cross the light bulb and back into the battery?”</td>
</tr>
<tr>
<td>Foregrounded: Explicit</td>
<td>“But how? But how? Would it turn back?”</td>
<td>(no examples of this category in the data)</td>
</tr>
</tbody>
</table>

The analytical process described here resulted in the identification of various stages of a disagreement between students about their mechanistic models, and a description of the richness of each stage, based on the explicitness of their opposition and the linguistics features students used to index disagreement, as described in the research by Pomerantz, Scott, and Goodwin.

**FINDINGS**

In this section, first I describe the mechanistic models of electric flow that each group students developed and presented, focusing on what happened to the electricity when connecting the wire to a battery and then disconnecting it. Then, I identify the structure of the disagreement (i.e., beginning, extension, and end; M. H. Goodwin, 1990), paying close attention to how the students attended to and disagreed about mechanistic elements of their models.

**Two different models of electricity flow**

Prior to discussing their ideas, each group (Yesenia and Elio; Toben and Grace) had the opportunity to build a complete electrical circuit using wires, batteries, and bulbs, and propose an
explanation for how the electricity flowed through it in order to turn on the bulb. Yesenia and Elio volunteered to share their model first, as exemplified in the following excerpt:

Excerpt 1:

1  Elio: The battery generates energy. But without the battery –
2  Yesenia: Battery – without battery it won’t light up – it won’t light up because because –
3  Elio: Energy will freeze.
4  Yesenia: Energy will freeze because there’s no energy.
5  Elio: Escribiste freeze mal. Es con silent ‘e’ (You misspelled freeze. It has a silent ‘e’).
6  Yesenia: Without the battery or the wires, none of the stuff ((moves hand in a circle above the complete circuit)) would work. But with – if you put all the pieces together it makes ((moves finger in a circle above complete circuit)) a circle of motion of energy that runs through the wires, through the battery ((touches the battery)), and through the light bulb ((points to the bulb)), causing the light bulb to light up.
7  Yesenia: Any questions?
8  Instructor: Any questions? Toben?
9  Toben: How does the battery generate?

When the instructor asked Grace and Toben if they had any questions, Toben asked, “how does the battery generate?” (line 12), prompting Yesenia to elaborate further:

Excerpt 2: (Yesenia, Lines 13-20)

How does the battery generate energy? (Toben: Mhmm) All batteries ((touches the battery)) have energy and the energy from the battery causes the whole thing to run ((moves hand in a circle above the complete circuit)) perfectly. So, so – a type of – energy comes from a type of uh iron. So, that iron they put it in the battery and that makes energy. So, when the energy ((touches the battery)) hits the wire it goes through the wire ((runs hand along one wire)), through the metal ((points to the bulb holder)) because energy can run through metal. So, it runs through the metal and it reaches the light bulb and it causes the light bulb to light up. Then it comes back ((runs hand long other wire)) and then it goes into the light bulb and into the battery again ((touches the battery)) and it keeps ((moves hand in a circle perpendicular to the table)) on going into a circular motion.

Yesenia and Elio reasoned that the battery is essential for the functioning of the circuit, having energy stored inside it (line 15-16), supplying that energy to flow through the circuit once the wires are connected (line 8 and line 17-19), and make the light bulb turn on (line 9 and line
Moreover, “the energy” will perpetually move in “a circular motion” (line 7, line 19-20) through the circuit, as long as the wires remain connected.

Yesenia and Elio also suggest that, if the battery were to be removed, or the circuit disconnected, the energy in the wires would stop in place (i.e., “freeze”) because there would be no more energy from the battery to push it through (line 6). When the instructor asked them to say more about what they meant by “freeze,” Yesenia stated:

Excerpt 3: (Yesenia, Lines 30-33)
So, when – so without a piece ((points to the battery)) the energy couldn’t go through it and the energy would freeze into place and it wouldn’t be moving. None of this would be moving. So, like we, say, we took – we disconnected this wire and left it like that the ( ) the energy would freeze and it wouldn’t be able to run through.

In this statement, Yesenia seems to allude to the need to ensure that all the circuit elements are well connected, given that removing elements would interrupt the connection and energy would stop moving (line 31). Also, based on her pointing (line 30), it is possible Yesenia thought that the battery is the circuit’s most important component, supplying the electricity and creating the continuous flow throughout the circuit. The model presented by Yesenia and Elio resembles the concept of an Electromotive Force (EMF) in circuits, which conceptualizes a battery as the pump responsible for moving the charges through the circuit; one important difference is that, in the canonical model, a battery creates an EMF in a circuit because of the difference in electrical potential between the battery’s poles, which Yesenia and Elio’s model did not account for.

When asked to present their model, Toben and Grace proposed the following short statement:

Excerpt 4: (Grace is holding a white board with a drawing of their model):
Grace: It starts from the battery. And then both wires at the same time ((runs fingers along the drawn wires)) go over here ((points to lamp)) and they make the light bulb go to light.

Grace briefly presented the foundations of their model; they expanded their ideas further in subsequent excerpts, as shown below. Toben and Grace proposed that the battery supplies the
electricity that travels through the wires (line 79). Additionally, Toben and Grace proposed that each side of the battery would provide a portion of the electricity (line 79), which would eventually meet at the light bulb. If one of the wires were to be disconnected, Toben and Grace reasoned that the electricity already in the circuit would find its way back to the battery (Excerpts 7 & 9, below). It would be sensible to infer that Grace presented a current-based model, in which the substance-like current runs through the circuit. However, Toben and Grace’s model is much more complex, including elements of a current-based model and an energy-based model, in which the difference in potential energy between the battery’s poles makes the circuit run.

Both groups treated electricity as a substance that moves through the circuit, and agreed that it is essential for all the components to be connected in order for the electricity to travel through the circuit and light up the bulb. As an important aside, both groups used the term “energy” when referring to the substance that ran through the circuit and made the bulb light up (i.e., electricity); I will use the two terms interchangeably to honor their lexical choice. However, these models differed in how they conceptualized the direction the electricity flowed in, and what made the electricity move through the circuit, creating potential points of disagreement. Yesenia and Elio suggested it flowed in a circular motion from one end of the battery to the other; Grace and Toben proposed each wire supplied electricity to the bulb and it eventually made its way back to the battery. Neither group discussed in depth the direction of the current’s flow, since the question of what happens after disconnecting the wire became more salient. Table 2.4 below summarizes their models, and Figure 2.1 offers a graphical representation of each.

Table 2.4: Summary of mechanistic models.

<table>
<thead>
<tr>
<th>Model Name (students)</th>
<th>Functioning: Connected</th>
<th>Functioning: Disconnected</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMF-like (Yesenia &amp; Elio)</td>
<td>The battery supplies energy and pushes it through the circuit in a circular motion. (Excerpts 1 &amp; 2)</td>
<td>Because the wire is disconnected, the battery cannot push the energy through, and it stops moving.</td>
</tr>
</tbody>
</table>
The battery supplies electricity, pushes it through each separate wire, and the electricity clashes at the lamp. (Excerpt 4)

The electricity makes its way back into the battery on its own, across the light bulb and through the other wire. (Excerpts 7 & 9)

*Meet & Return* (Toben & Grace)

<table>
<thead>
<tr>
<th>Functioning: Connected</th>
<th>Functioning: Disconnected</th>
</tr>
</thead>
</table>

**EMF-like**
(Yesenia & Elio)

**Meet & Return**
(Toben & Grace)

Figure 2.1: Graphical representations of the groups’ mechanistic models, rendered by the researcher.

Yesenia and Elio’s *EMF-like* model proposed that the electricity would immediately stop flowing once the wire was disconnected from the battery, since the battery would not be able to supply more electricity to push through whatever was already in the wires. Whereas, Grace and Toben’s *Meet & Return* model claimed that, after disconnecting the wire, the electricity already flowing through the circuit would continue to do so until all of it returned to the battery; while there are multiple conditions that could explain this idea (e.g., a “height” difference that would make the electricity move towards the “lower” part of the circuit), Grace and Toben did not explicitly describe the activity behind this process. These differences about how the electricity would return to the battery became the primary point of contention for the groups.

**Beginnings of the disagreement: attending to differences between models**

Again, both groups laid out similar setup conditions for the mechanisms responsible for the functioning of the circuits, given that they identified the same macroscopic (i.e., batteries, wires,
bulbs) and microscopic entities (i.e., electricity), and the need for all components to be connected through wires. However, according to their models these entities participated in significantly different activities (see Figure 2.1, Table 2.4). Immediately after Grace presented her and Toben’s model (lines 79-80), Yesenia asked a general question about how the battery worked:

Excerpt 5:

81 Yesenia: And why - how does the battery without any of the uh of the wires? How would it work?
82 Toben: Grace, it’s your (   )
83 Yesenia: I got asked that answer when uh Toben um asked me his questions.
84 Grace: How does it work?
85 Yesenia: How does it work if eh – there's no wires, no batteries, or a light bulb?
86 Grace: U:::h
87 Elio: I think that’s a trick
88 Instructor: Do you understand the question?
89 Grace: Uh -
90 Yesenia: I said it in my answer when Toben- when I was presenting and Toben asked me the question
91

Through posing a question similar to Toben’s (i.e., “how does the battery generate?” line 12), Yesenia requested Grace’s model, while attending to the properties of the battery as an important macroscopic entity. Specifically, Yesenia’s wh-question could be seen as an attempt to understand how Grace conceptualized how the battery produced the electricity on its own (lines 81-82), key for determining the system’s setup conditions. Moreover, Yesenia’s question focused on how the properties of the battery contributed to the setup conditions of the mechanism.

It is not clear whether Yesenia agreed or disagreed with Grace’s model from the outset (lines 81-82), but there are multiple linguistic features in this excerpt that index disagreement, setting up the upcoming opposition. Yesenia began her turn with wh-questions that addressed how the battery worked (line 81), which could serve a double purpose: Yesenia initiated a request of information from Grace and Toben to see how their model treats the battery’s function within the circuit (i.e., how it produces the electricity that will flow through the circuit); at the same time,
because it included the absolutes “any of the wires,” this question indexed a potential conflict. Instead of answering the request, Grace summarized Yesenia’s question (line 85), perhaps in an attempt of repair, which Yesenia then repeated and highlighted the battery’s isolation by removing the other entities from the circuit (line 86). Yesenia seemed determined to request more information about Grace and Toben’s model, reflected in the wh-questions and negative absolutes related to the mechanism’s entities, such as bulbs and wires. These linguistic features indicate an early oppositional stance that would set the background for upcoming disagreement.

Yesenia’s turns resemble what the Accountable Talk and TAP frameworks would consider productive for arguing about scientific phenomena: she presented a model, listened to her peers’ model, identified an area she wanted to know more about, and engaged with Toben and Grace’s explanation of the circuit. From the linguistic features in her turns, it is reasonable to infer that Yesenia expressed some opposition, although it is not clear towards which ideas. However, while Yesenia’s turns directly questioned some of the setup conditions in Toben and Grace’s mechanistic model (i.e., how the battery generated energy on its own), and potentially disagreed with their responses, both turns were oriented to disprefer disagreement as the consequent action. Specifically, Yesenia attempted to mitigate any potential conflict through justifying why she had posed the two questions in the first place (lines 84 and 91-92).

The question about the battery’s function in or out of the circuit was further contested in the next exchange. Toben or Grace did not have an opportunity to address the previous requests, since the instructor interjected to repeat Yesenia’s question in case Grace did not understand it:

Excerpt 6:

<table>
<thead>
<tr>
<th>Line</th>
<th>Speaker</th>
<th>Text</th>
</tr>
</thead>
<tbody>
<tr>
<td>93</td>
<td>Instructor</td>
<td>So I think – if I – if I understand correctly, Yesenia, your question is: if the battery’s –</td>
</tr>
<tr>
<td>94</td>
<td></td>
<td>if the cables were not connected to the light bulb and the battery, if they – how</td>
</tr>
<tr>
<td>95</td>
<td></td>
<td>would it work?</td>
</tr>
</tbody>
</table>
Yesenia: How would it (circuit) work? Would it (electricity) freeze? Would it (electricity) still keep running? (moves hand in a circle above the table)

Instructor: o:h it's circular

Yesenia: or would it (circuit) turn off?

Grace: It (circuit) would turn off.

Instructor: It (circuit) would turn off.

Yesenia: And what happens to the uh - to the energy?

Grace: Um, um, there would - there would - there would be no – no energy, um –

Toben: *Why? ((smirk))

Yesenia: *Why? Why wouldn't there be any energy?

The exchange begins with the instructor’s revoicing move to repeat Yesenia’s question about the battery’s role in the circuit (lines 93–95), which she used to shift the conversation’s focus to address what happened to the electricity after disconnecting the wire. Specifically, in line 96, Yesenia increased the level of specificity about what happens to the electricity already in the wires once the battery was disconnected. Through her questions, Yesenia requested more information about Toben and Grace’s model, inviting them to explain the activities these entities (e.g., battery, wires, electricity) engaged in once the battery was disconnected, and provided alternative explanations for Grace to choose from (e.g., “would it (electricity) freeze? Would it (electricity) still keep running?”, line 96). Grace answered Yesenia’s question “it (circuit) would turn off,” (line 99), addressing the outcome of the disconnect (i.e., termination conditions). Grace’s answer agreed with Yesenia’s idea that the light bulb would turn off (Excerpts 2 & 3), but did not explain what happened to the electricity, prompting Yesenia to press again for an explanation (line 101). Grace claimed that disconnecting the wires would result in “no energy” (line 102), suggesting the wires would be free of electricity.

Building on the instructor’s interjection, Yesenia continued to request information about Toben and Grace’s mechanistic model, until she heard an idea she disagreed with. Specifically, Yesenia began by posing a question that focused on how the circuit would work without a battery connected to it (line 96). Before Grace or Toben have an opportunity to answer the
question, Yesenia presented three consecutive questions that allowed her to maintain control of the floor: “Would it (electricity) freeze? Would it (electricity) still keep running? Or would it [circuit] turn off?” (lines 96 and 98). In addition to requesting information and retaining the floor, these questions contained possibility modals (i.e., words indicating likelihood of an event happening) that provided options for Grace and/or Toben to choose from when answering them. All three linguistic features in Yesenia’s turn (i.e., questions, floor bids, modals) have been shown to index disagreements (M. H. Goodwin, 1990; Scott, 2002), and Yesenia deployed them together in a complex way. While the directness and timing of the questions indexed opposition from Yesenia, offering explanatory choices to address her questions about activities could be interpreted as an attempt to offer help and disprefer disagreement as the consequent action. Grace chose one of the options Yesenia presented, “it [circuit] would turn off” (line 99), which, again, did not describe what happened to the energy. Yesenia’s subsequent wh-question inquires into the outcome of the energy already delivered by the battery (line 101), and, finally, Grace spoke to the electricity’s fate: “there would be no – no energy” (line 102).

Up until this point, Yesenia’s turns, while direct, focused on requesting information from Grace through multiple strategies (e.g., asking questions, considering alternatives). However, Grace’s assertion that there would be no energy (line 102) is a turning point in the discussion and marks the beginning of the disagreement. Much like Goodwin (1990) observed, Grace’s answer to the question propelled the explicit disagreement, rather than working towards consensus. Yesenia’s subsequent turn latched onto Grace’s response, presenting two questions in quick succession, “Why? Why wouldn't there be any energy?” (line 104), providing no opportunity for Grace to respond or repair. Of particularly import is Yesenia’s second question, “Why wouldn’t there be any energy?” that includes multiple indices of disagreement. Specifically, Yesenia
constructed a wh-question that requested information, relying on a prediction modal combined with a nonaffixal negation (“wouldn’t”), followed by an absolute statement about the energy in the wires (“any energy”). The presence of all these markers of disagreement indicate that Yesenia was disputing Grace’s explanation. Inherent in her question is Yesenia’s surprise by Grace’s claim that there would be no energy in the wires (line 102) despite some having entered the wires when the battery was connected (line 79). Therefore, Yesenia engaged with, evaluated, and, through multiple linguistic features that index disagreements, disputed the electricity’s activity that Grace proposed in order to explain why the circuit turned off. Yesenia relied on linguistic features that serve of index and enact a disagreement, without foregrounding the opposition. Moreover, this exchange exemplifies the importance of counting on an analytical toolkit capable of recognizing the subtlety with which the disagreement was enacted; an analytical lens that focuses exclusively on explicit statements of disagreement would have likely missed the productive epistemic work done by Yesenia and Grace through their interaction.

Disagreeing about what happens to the electricity

As discussed above, Yesenia began her inquiry by asking questions about the circuit and the electricity (lines 81, 96), requesting more information from Grace about her and Toben’s model. By the end of Excerpt 6, Yesenia had identified a difference between the two proposed models, and took initial steps towards addressing it. As I show below, Yesenia’s question and Grace’s response constitute the first step of the disagreement over what the energy is doing in the circuit:

Excerpt 7:

105 Grace: It's because if – if it don't – it don't – if you take off the battery um the energy
goes to the battery, to the light bulb, or both. And if the wires were connected
((brings index fingers together))
107 the battery uh the electricity could go through here ((points to clamps)) and
make the light bulb worked.
108 Yesenia: = But how does [the -
109 Toben: [Why?
110 Yesenia: [the – how does the energy um cross the light bulb and back into
the battery, and then do it again and again? How does it cross?

Grace reported a mechanistic explanation that expanded on her previous ideas about what happened when the circuit was disconnected. Specifically, Grace described in detail the activities the circuit entities were involved in, proposing that the electricity “goes to the battery, to the light bulb, or both” (line 106). This explanation highlighted the activity that Yesenia had been asking about (i.e., flowing back to the battery), although it did not describe what would make the electricity go back to the battery. Additionally, Grace contrasted how the electricity behaved in an open circuit to how electricity flowed through a complete circuit, allowing for the currents to meet at and activate the light bulb (lines 106-107). Yesenia’s follow-up question acknowledged Grace’s idea, and asked for clarification on what pushed the electricity across the light bulb. In essence, Yesenia seemed to be asking Grace to describe the activity that would push the remaining energy back into the battery, after the wire is disconnected. With this move, Yesenia evaluated Grace’s explanation at a very detailed level, considering all the possible activities responsible for the mechanism, and challenged her ideas, as I will show below.

After listening to Grace’s explanation, Yesenia offered the very first discourse marker of negation of the exchange, and got the disagreement going. With a single “but” in her question (line 108), Yesenia began to highlight the discrepancy between her and Grace’s explanatory model. Moreover, Yesenia followed-up with two consecutive wh-questions that underlined how Grace’s explanation did not specify what made the electricity return to the battery once the wire was disconnected (lines 110-111); it is possible Grace had an implicit notion of the mechanism that would return the energy to the battery, although it was not articulated. And yet, while starting her turn with a linguistic feature that foregrounded the disagreement, Yesenia presented an extension of Grace’s idea (i.e., moving through the battery “again and again”), and a question (line 111) that offered Grace an opportunity to reconsider and refine her model. In effect,
Yesenia offering a new scenario for Grace to consider could be interpreted as an attempt to disprefer and/or mitigate the opposition, while still making explicit her disagreement.

Once again, the instructor tried to resolve any possible confusions by highlighting the differences between the two models, which opened the door for the disagreement to be sustained by questioning an alternative explanation, as shown in the following excerpt.

Excerpt 8:

112 Instructor: Well, but - I think their idea is different. I think that - Grace, I think that what you said is that the ene - that the electricity or the energy moves through both vines –
113 so, Grace calls them vines - they move through the vines and they meet up here ((points to light bulb)). But then your idea (Yesenia) is that they just move kind of like in a circle [around.
116 Toven: [Why does the wires, wires out there (?)
118 Instructor: [and around and around.
119 Yesenia: So eh eh in the battery if the energy goes together ((moves hands towards each other until they meet)), why would it turn back ((moves one hand back down))? If you disconnect one of the wires, how would it turn back to the battery?
120 Toven: Grace, why? ((smirks))
122 Instructor: What do you think, Toven? What's your idea?
123 Toven: That it - the - if it turned off the - the batt- the energy would go back into the battery ((traces drawn wire with his finger back to the battery)).
125 Yesenia: = But [how?
126 Instructor: [How would the energy go back to the battery, do you think?
127 Toven: By going to the light bulb, and then going through the wires, back [to the battery ((traces drawn wire with his finger back to the battery)).
128 Yesenia: [But how? But how? Would like it turn back?

The instructor summarized the differences between the models in terms of the direction in which the electricity flowed (i.e., coming together, line 114-115; moving in a circle, lines 115-116). However, the instructor seemed to miss that Yesenia had asked Grace to describe the activity that made the remaining electricity travel through the bulb and back into the battery (Excerpt 7). Building on the instructor’s summary, Yesenia distinguished between the direction...
the current flowed in and what propelled it through the circuit (lines 119-120). Yesenia’s first question (“why would it turn back?”) addresses the role the wires play in the flow of current. Specifically, Yesenia seems to have interpreted Grace’s model as suggesting that a wire that originally carried current to the light bulb would reverse its function after disconnecting the battery, now carrying current back to the battery. It is important to remember that, based on Yesenia and Elio’s EMF-like model, each wire serves a specific function in making the current flow through the circuit: one wire supplies the electricity to the bulb, and the other one brings it back to the battery. It might have been confusing for Yesenia that a wire that supplied electricity to the bulb would all of a sudden switch its function and move electricity from the bulb to the battery. Yesenia’s second question temporarily accepted Grace’s explanation that the wires could reverse their roles (i.e., move electricity from the bulb and back to the battery), for the sake of the argument, and explicitly interrogated the activity responsible for pushing the remaining energy back into the battery (line 120). As stated before, the EMF-like model claims the battery’s continuous supply of energy propels the electricity through the circuit, which is why the electricity stops when the battery is disconnected. Through her question, Yesenia was asking Grace to specify an equivalent activity in the Meet & Return model.

Yesenia’s concern with unpacking the activity that moved the electricity through the circuit in the Meet & Return model became clearer once Toben explained what happened to the electricity after disconnecting a wire. Yesenia addressed her questions to both Grace and Toben, although Toben tried to deflect attention to his sister (line 121), possibly to avoid uptake. Still, the instructor wanted to get Toben more involved in the conversation (line 122). Toben agreed with Grace’s claim that disconnecting the wire would result in the electricity moving back to the battery (lines 123-124). While mechanistic in nature, Toben’s explanation did not explicitly state
the activities or conditions that would bring the electricity back to the battery. As explained below, Yesenia rejected Toben’s answer through her question, “but how?” (line 125), which also functions to request further details about the activity at play. Toben answered Yesenia’s question by describing the electricity’s path, focusing on how the electricity that remained on the disconnected wire would travel to the light bulb and from there through the connected wire back to the battery (line 127). Thinking that Toben had not addressed her questions, Yesenia deployed three consecutive queries that interrogated the activities in his mechanistic explanation responsible for moving the electricity when the wire was disconnected (lines 128-129).

Related to how students enacted the disagreement, at first, Yesenia used several linguistic features to perhaps mitigate the opposition, but then foregrounded it. Despite the directness of Yesenia’s early questions, there were only a few linguistic features present that index disagreements. Specifically, Yesenia posed two wh-questions in quick succession that contained prediction modals (lines 119-120), which questioned Grace and Toben’s model. The timing of these questions allowed Yesenia to remain in control of the floor, and did not offer Toben and/or Grace an opportunity for repair or rebuttal. Combined, Yesenia’s moves indexed opposition. However, these two questions were constructed in a way that tried to highlight for Toben and Grace the mechanistic activity Yesenia thought was missing from their model (i.e., propulsion). This attempt to make visible what she was asking for (e.g., “if the energy goes together, why would it turn back?” line 119) could be seen as Yesenia giving Grace and Toben opportunities to reconsider and perhaps refine their ideas. Thus, following directness with alternatives could be interpreted as Yesenia shaping her turn to mitigate the current disagreement.

In the second part of the excerpt (lines 123-129), the disagreement’s intensity increased. Specifically, Yesenia used the discourse marker of disagreement “but” for the second time in the
discussion (line 125), and latched it to Toben’s first attempt at explaining his observations, emphasizing the intensity of Yesenia’s rejection of his explanation. Just as before, Toben’s explanation that “the energy would go back to the battery” (lines 123-125), gave Yesenia an opportunity to extend the dispute and continue to focus on the activity that would push the electricity through the circuit despite the disconnection. Toben tried once more to answer Yesenia’s question by adding more details and, before he finished his idea, Yesenia interjected with a series of new questions (lines 128-129) with more linguistic features that index disagreement. The overlap between Yesenia’s question and Toben’s statement indicates that Yesenia made a bid for the floor, an act of opposition that was intensified by the question, “But how?” (line 128), which contained a marker of disagreement. Yesenia quickly stated the question a second time, using repetition to increase the urgency of her request.

Based on the way Yesenia used the question “but how?” three times throughout this excerpt, it would be sensible to conclude that she foregrounded the disagreement between their ideas and rejected elements of Toben and Grace’s Meet & Return model. However, Yesenia ended her turn with a question for Toben, “would like it turn back?” (line 129), containing a possibility modal that highlighted her request for a pushing activity and the option for Grace and Toben to present one. Therefore, Yesenia uses a host of linguistic markers to create a layered way of disagreeing with her peers’ mechanistic model, trying to make visible the activity she thought was missing from their explanation and giving them opportunities for refining their ideas.

**Bringing the disagreement to a close: refining models or acquiescing?**

At this point in the disagreement, Yesenia had rebuked Grace and Toben’s model several times, and neither had produced the answer she had been looking for. In an attempt to support Grace and Toben bolster or change their ideas, the instructor connected and disconnected the circuit again, focusing their attention on how the bulb turns off after the disconnect:
Excerpt 9

139  Instructor: What do you two think? Like, I disconnected this ((points to the right wire)), what happened to the energy?
140  Toben: That -
141  Yesenia: Would it freeze or turn back to the battery?
142  Toben: Turn back to the battery.
143  Instructor: It came back here ((points to the battery))? Why do you think that?
144  Toben: Becaus - coz the um energy from the light bulb goes to the wires because the
145  Instructor: metal things (alligator clamps) are connected to the wires so it will light up – it will go back.
146  Yesenia: OK
147  Grace: I have a question for my brother, too
148  Yesenia: So uh –
149  Instructor: Wait (Yesenia), Grace has a question for her brother, Toben.
150  Grace: ( ) for – how um – how does – how does – how does the electricity from(?) to
151  Instructor: the battery – reach to the light bulb?
152  Toben: The battery goes through the wires.
153  Yesenia: But how does it cross to the light bulb? Because –
154  Toben: [uh – through the wires.
155  Yesenia: [Through the wires? There’s no wire connecting here ((points to the battery)) to the light. [So, what’s happening?
156  Toben: [coz - It’s going through the metal thing.
157  Yesenia: It goes through the metal and the metal can attract energy –
158  Grace: Why are you (Toben) hiding your face?
159  Yesenia: So the light bulb because of this wire will turn off. So, actually, the uh – it (electricity) doesn’t
160  Instructor: turn back into the – to the – to the – it (electricity) actually doesn’t turn back to the battery, it (electricity)
161  Toben: just freezes, like, it (electricity) stays still because without the battery or nothing connected
162  Yesenia: it’ll – it (circuit) would all fall apart. Like, the energy would stop running and –
163  Instructor: because there’s no currents to uh – to the move the energy and so the energy
164  Toben: would freeze and won’t – it wouldn’t be moving so it (electricity) wouldn’t be moving into the
165  Yesenia: light bulb. If I take this off –
166  Instructor: I can hold this (circuit) for you.
167  Yesenia: So, I take this off - so if I take this off it would um - it would um - the energy would
168  Instructor: freeze and it wouldn't go in the middle and the reach the light bulb, which causes
169  Toben: it to light up, and then back to the light bulb, it wouldn't do that because
170  Instructor:
there's no currents. Because if we just took off one little piece it would uh stop working.

After the instructor’s question, Yesenia succinctly summarized the two positions that were being discussed in the form of a question (line 142), perhaps giving Toben a chance to revise his and Grace’s model in light of the preceding exchanges and experimental observations. Toben’s response to the instructor’s question was concordant with his previous statements about how the electricity that remained in the wire that was disconnected traveled through the light bulb and into the connected wire in order to return to the battery (lines 145-146). This time, however, Toben added a new detail to his explanation he had not mentioned before, specifically that the metal alligator clamps from the wires were connected to the lamp base where the light bulb rested (line 146). Toben seemed to allude to the conductive nature of metals to explain why the electricity is able to flow to and through the bulb. Toben’s new idea was followed by a question from Grace, which seemed to also address the issue of what propelled the electricity from the battery and “reach the light bulb?” (line 152). Toben’s response again focused on how the electricity traveled through the circuit, rather than elaborating on what pushed it through (line 153), giving Yesenia another opportunity to ask how is it that the electricity crossed the bulb (line 154). Toben insisted once more that the wires made the electricity cross the light bulb (line 155), and that the metal parts of the circuit allowed for the electricity to flow through the different components (line 158). Absent from Toben’s response is an explicitly stated reason for why the electricity keeps moving. From Yesenia’s perspective, the electricity needed to be pushed through the circuit by the battery, which is why she seemed intent on asking Toben what would keep the electricity flowing after disconnecting the wire (line 156).

Seemingly frustrated by Toben’s response, Yesenia described her EMF-like model to the whole group, illustrating her full disagreement with the Meet & Return model. Yesenia began by
agreeing with Toben and Grace’s assertion that the light bulb turned off (line 161), but then refuted the idea that this happened because the electricity turned back to the battery (line 162). Instead, Yesenia argued that the electricity “freezes, like, it stays still” because the wire had been disconnected from the battery (line 163), eliminating the “currents” that would move the energy into the light bulb (lines 165-168). Therefore, by specifying the function of the battery in a complete circuit (i.e., acts as an electromotive force that moves the current around), Yesenia called attention to the activity in the Meet & Return mechanistic model responsible for moving the electricity through the circuit, which nor Toben nor Grace had explicitly described before.

Throughout this excerpt, Yesenia foregrounded the disagreement as she asked multiple times for an explanation for what would push the electricity across the light bulb after disconnecting the wire. In her first turn of the excerpt, Yesenia followed Toben’s claim that the electricity would move through the wires with a wh-question that began with an explicit marker of negation (“but”, line 154), in a move that underlined the disagreement’s foregrounded nature. Before she was able to offer a prefatory statement about her question, Toben’s response, “through the wires” (line 155), overlapped with and interrupted Yesenia’s turn. This was the first time that Toben or Grace interrupted Yesenia’s turn and gained control of the floor, which I interpret as the disagreement’s intensity had reached a climax. Yesenia quickly responded to Toben’s claim (lines 156-157), once again overlapping and latching her rhetorical question to gain control of the floor. Unlike previous excerpts, however, Yesenia repeated Toben’s statement in the form of a question, “through the wires?”, which could be interpreted as her identifying the portion of his statement she found problematic. In fact, Yesenia followed her rhetorical question with the assertion that the wire had been disconnected; again, this is relevant to Yesenia because, according to her EMF-like model, the battery pushed the electricity through the circuit and a
disconnection would interrupt that flow. Finally, the timing of her statement framed Toben as incapable of repairing his speech, a move that is foundational to opposition (M. H. Goodwin, 1990). All the linguistic features that Yesenia deployed shaped her turn to foreground the disagreement and express her opposition to Toben’s explanations. And yet, Yesenia ended her turn by posing an open-ended question, “What’s happening?” (line 157), which offered Toben another opportunity to reconsider his reasoning and, therefore, access to the discussion. This offer, in effect, served to mitigate the intensity of the disagreement that Yesenia was foregrounding.

Toben presented one more explanation to support his reasoning: it goes through the metal and metal can attract energy (line 158). Toben’s response identified properties of some of the entities involved in the mechanism (metallic alligator clamps and leads on bulb holder), but did not elaborate on the activity responsible for the energy to continue flowing through the circuit when one of the wires is disconnected. The mismatch between Yesenia’s question and Toben’s answer seems relevant, given that it set up Yesenia for bringing the disagreement to a close by stating a complete mechanistic explanation without being prompted (line 161-172). In this last turn, Yesenia’s 181-word response did not acknowledge nor address Toben’s reasoning, eliminating any possibility for him to refine his ideas.

After a brief pause that followed Yesenia’s statement, Toben turned to Grace and asked:

Excerpt 10

173 Toben:  Grace, what’s your opinion?
174 Grace:  I don’t have an opinion. How about you?
175 Toben:  It was your turn.
176 Instructor:  Do you agree with what Yesenia is saying – Yesenia is saying? Or Elio is saying? Do you agree with them or do you –
177 Toben:  Grace, do you agree?
178 Grace:  uh I – uh I agree. Do you agree?
179 Toben:  Yes!
180 Instructor:  Why do you agree? Like, [why do you think that what she’s saying makes

44
In this final excerpt, Toben and Grace worked towards a resolution of the disagreement, asking each other to articulate their agreement with Yesenia’s explanation. The exchange began with Toben and Yesenia asking each other to state their “opinion” about Yesenia’s idea (lines 173-175). The back and forth, with neither of them committing to a position, could be interpreted as acts of uptake avoidance, in which both students deflect the request for their position. When the instructor explicitly asked whether they agreed with Yesenia and Elio’s model (lines 176-177), Toben first asked Grace whether she agreed with Yesenia (line 178). Grace stated that she did agree with Yesenia’s idea, and immediately asked Toben whether he agreed (line 179), which Toben answered with an emphatic “Yes!” (line 180). But rather than accepting these statements as a resolution to the disagreement, the instructor asked Toben and Grace to justify their agreement with the EMF-like model (line 181). This request from the instructor precipitated another sequence of Grace and Toben asking each other why they agreed with Yesenia (lines 182-186), without either presenting their reasoning nor committing to a position. While uptake avoidances have been reported as indexing disagreements (Scott, 2002), in this case this linguistic feature could be working as stopgaps, allowing Toben and Grace to displace the locus of agreement to their partner or make time to construct a reasoning for their position.
The instructor reminded Toben and Grace that their agreement or disagreement with Yesenia’s explanation should be based on the discussions in their small group (line 187). Still, Toben and Grace asked each other for their individual stances (lines 188-189), perhaps once again sidestepping taking a position on the issue. Toben broke the cycle of uptake avoidances by stating that he did agree with Yesenia’s idea “because uh it [electricity] will freeze because uh if it [electricity] goes back –” (line 190), but is interrupted by Yesenia (line 191) before he can explain why he finds the EMF-like model more compelling. While not fully articulated, it seemed like Toben was beginning to justify his position by contrasting it to the outcomes of the Meet & Return model (i.e., electricity would travel back to the battery; line 190). However, Yesenia interrupted Toben and, therefore, difficult to know what he was about to contribute to the discussion. Still, the nature and the timing of the interruption seem relevant to bringing the disagreement to an end for various reasons. First, Yesenia deployed the non-affixal negation of the predictive modal (i.e., “it wouldn’t work,” line 191) perhaps as a way to reaffirm her claim that the Meet & Return model does not explain their observations, therefore opposing Toben and Grace’s earlier reasoning. Additionally, the timing of Yesenia’s interjection kept Toben from fully presenting his reasoning for why he agreed with her. Overall, this move seems to have allowed Yesenia to stop any potential dissent that would have extended the argument, as happened in excerpts 7 and 8, and capitalize on Toben’s partial agreement to promote her idea.

In the end, Toben agreed with Yesenia’s statement (line 192) that “it wouldn’t work.” Toben’s final agreement suggests he forewent the Meet & Return model and seemed to accept Yesenia’s EMF-like model; this resembles the ways M. Goodwin observed children end disputes by accepting other’s ideas (1990). However, since Yesenia interrupted Toben when he was about
to present his reasoning, it is difficult to know if he actually refined his ideas, or if he just accepted Yesenia’s position in order to end the dispute, as M. Goodwin also observed.

**DISCUSSION AND CONCLUSION**

In this study, I identified and articulated the structure and elements of a disagreement between students’ mechanistic models on how electricity flowed through a circuit, leading to three main findings. First, as demonstrated through the analysis, students’ mechanistic models addressed multiple aspects of the phenomena that they thought were salient. Specifically, students agreed on the different entities (e.g., energy, wires, battery) and conditions (e.g., battery stores energy) that give rise to electric flow through a circuit, but disagreed about two fundamental activities: direction of flow, and what happens to the electricity after disconnecting the battery. Second, the differences between students’ models created the conditions for students to engage in a disagreement about the functioning of the circuit, particularly about whether the electricity would stop or make its way back to the battery. However, this disagreement did not resemble the ways opposition has been often portrayed by the science education literature, especially according to the Toulmin’s Argument Pattern (TAP). Rather than relying on explicit statements of opposition (e.g., “I disagree with you”), students resorted to various linguistic features to present rebuttals, such as questions with markers of negation in them (e.g., “why wouldn’t there be any energy?”). Finally, while students made clear their disagreement with each other’s models, they enacted these oppositional discursive moves in ways to avoid future or lessen current disagreements. Thus, this analysis reveals the rich and complex discursive and epistemic work these students did when sharing, evaluating, and disagreeing about mechanistic models, most of which would have been missed by, say, applying the TAP to the discussion.
Presenting and Evaluating Mechanistic Models of Electric Flow

The exchange discussed in this article centered around students presenting and evaluating their explanatory models for how and why electricity flowed through a circuit, in particular the effect of disconnecting wire from the battery. As the data show, students’ models were mechanistic in nature, given that they considered setup and termination conditions, and accounted for the entities and activities that gave rise to their observations (MacHamer, Darden, & Craver, 2000; Russ et al., 2008). And, as demonstrated above, the disagreement between Elio, Yesenia, Grace, and Toben arose from differences between the elements of their mechanistic models. Specifically, these students realized that the activities they described about what would happen to the electricity once the wire was disconnected contradicted each other and needed to be resolved. Had students proposed a causal explanation (e.g., connecting the battery makes the bulb light up), they would have not recognized they disagreed about certain mechanistic activities, and could have missed an opportunity for discussing and refining their ideas.

Therefore, I argue that constructing, sharing, evaluating, and disagreeing about these mechanistic models created opportunities for students to engage in valuable epistemic practices that are central to science. Students had rigorous conversations about the two models they presented, identifying discrepancies between mechanistic elements that could compromise the models’ explanatory power, an important step in refining models. For example, Yesenia’s sustained examination into what propelled the electricity through the circuit once the battery was disconnected created opportunities for students to ask questions about the phenomenon, collect and interpret evidence, and construct and evaluate evidence-based explanatory models. Moreover, engaging in this type of discussion allowed students to refine their ideas and develop their conceptual understanding of circuits. An example of this conceptual growth is how, through her sustained questioning that addresses mechanistic elements, Yesenia’s ideas about the energy
freezing went from a causal account that disconnecting the wire would make the energy freeze (excerpt 3), to the mechanistic claim that disconnecting the wire would take away the currents that move the energy through the circuit (excerpt 10). In essence, disagreeing about mechanistic activities created “a public arena where arguments can be explicated more fully and made public, looked at by others, interrogated, and developed further” (Michaels et al., 2010, p. 6).

Finally, the disagreement analyzed in this article might have been supported by an impossibility for these students to really comprehend each other’s mechanistic models. In a way, this disagreement parallels Thomas Kuhn’s description of paradigm in science, particularly subscribing to and arguing from a specific set of understandings and expectations of nature (T. S. Kuhn, 1970). For scientists to reckon with the limitations of their theoretical commitments and assumptions, first they need to be aware of possible anomalous observations from their experiments that cannot be explained by current theoretical paradigms (T. S. Kuhn, 1970, p. 62). Otherwise, the kinds of discussions between scientists that seek theoretical consensus and, lead to a paradigm shift, will be thwarted by incommensurable paradigms and lack of common ground. Similarly, the students described in this study seemed to find themselves in two different paradigms about how electricity flowed through a circuit, paradigms represented by each model and their account for what moves the electricity through the circuit with or without the battery. Examples reported in the literature portray students disagreeing about the evidence and/or warrants that support a claim that is common across paradigms (e.g., Erduran et al., 2004; J. Osborne et al., 2004). For me to offer a counter-claim with evidence, you and I need to agree on what we are seeing for the counter-claim to make sense. Meanwhile, the disagreement analyzed in this study seemed to stem from incommensurable paradigms and, therefore, required students to choose one of the two models, the one they thought had the highest explanatory power.
Managing the explicitness and intensity of the disagreement

Students disagreed with each other’s mechanistic models through a wide range of linguistic features that indexed opposition. For example, Yesenia’s question, “Why wouldn’t there be any energy?” (line 104) both indexed a portion of Grace’s claim she found problematic and requested more information from Toben and Grace. And, on a handful of occasions (lines 108, 125, 128, and 155), Yesenia initiated her question with the explicit marker of negation “but,” making her opposition more evident to her peers. As presented in the analysis, all these discursive moves served to highlight differences and opposition between students’ mechanistic models, making it clear that they disagreed with each other. Moreover, I argue that these explicit disagreements created some of the conditions that kept students accountable to the learning community, as they listened to and engaged with each other’s explanations, and accountable to the standards of reasoning, as they evaluated the plausibility of the two mechanistic models.

But just as students foregrounded their disagreements, they also made discursive choices that tried to decrease the intensity and/or possibility of disagreements about their models. In fact, most of the turns that foregrounded the opposition also contained discursive moves that tried to avoid any conflict with other students. For example, when Yesenia asked Grace “but how does the energy cross the light bulb?” (lines 108-110), Yesenia was explicitly inviting Grace to contribute to the conversation, despite clearly disagreeing with her; Yesenia’s was not a rhetorical question. Even when Yesenia used more explicit markers of opposition to express her disagreement, she still presented a second question that offered an alternative idea for Toben to consider and refine his thinking. The students seemed to strive for a balance between highlighting and addressing the differences between their models, and doing so in a way that signaled to their peers that their intention was not to be inconsiderate. This tension highlights the
importance of attending to the epistemological aspects of arguments, as well as the interpersonal ones, particularly when students seem predisposed to avoid conflicts with peers.

Based on these data, I argue that this balancing act between explicitly disagreeing and not being abrasive could have acted as another key element for creating and maintaining opportunities for students to continue participating in the process of co-constructing knowledge about circuits. For example, throughout excerpt 6, Yesenia increased the intensity of her opposition, as she went from requesting information (line 96) to explicitly contradicting Grace’s idea (line 104). And yet, both turns included questions that continued to ask Toben and Grace for their ideas and reasoning, effectively keeping them in the conversation. Regardless of Yesenia’s position in that moment, her oppositional yet inviting questions offered Toben and Grace opportunities to reflect and elaborate on their reasoning, rather than shutting their ideas out. Disagreements that include these types of invitations to remain engaged in the discussion stand in sharp contrast to exchanges in which students are concerned with crafting the most infallible argument, as TAP would require, perhaps disregarding whether their peers can continue to be part of the conversation. Had Yesenia presented her 181-word mechanistic explanation (lines 161-172) at the first sign of disagreement, it is not difficult to imagine how Toben and Grace might have felt silenced and, therefore, excluded from the discussion. Instead, Yesenia engaged in some of the Talk Moves (Michaels et al., 2010) we would expect effective teachers to use to support students engage in Accountable Talk. Therefore, through managing the explicitness of disagreements, students exercised a form of “ethic of epistemic care” (Krist, 2016, p. 302), through which they attended to each other’s presence and participation in their discussion about circuits. For these students, this was not a competition for who was right, but rather a community-based enterprise in which the exchange of ideas was paramount.
Implications

This study’s findings make valuable scholarly and practical contributions for identifying and investigating disagreements in science learning environments. As discussed before, science education recognizes disagreements between students about their ideas as central to co-constructing knowledge. However, the focus has remained on explicit statements of opposition (Erduran et al., 2004; Michaels et al., 2010, 2008; Osborne et al., 2004), while other forms and elements of disagreements have not been described in much depth. The detailed analysis of the disagreement between Yesenia, Elio, Toben, and Grace presented here sheds light into the nuances and subtleties with which students can disagree with each other. Specifically, questions, overlaps in speech, and modals, to name a few, can be deployed by students to index opposition to their peers’ ideas and create the conditions for them to engage in productive epistemic practices. Students can also organize their turns of talk to prefer specific following actions from their peers, and even modulate the intensity of their position. The set of linguistic features described here that index opposition offers a finer-grained analytical toolkit for identifying and describing the ways in which students could be engaging in disagreements and, therefore, negotiating differences in models and/or reasoning. Therefore, these tools for analyzing students’ talk could yield substantial insight into whether and how students share and evaluate ideas.

This study’s findings provide additional insight into how the practices of presenting and evaluating mechanistic models emerge in a community of learners to achieve specific epistemic goals. As Lave and Wegner argue, all practices of a community are generated and, therefore, bound to the sociohistorical circumstances of that community (Lave & Wenger, 1991). Specific to the K-12 science classroom, it is important to understand how science disciplinary practices are interpreted and become meaningful to students in order to achieve specific epistemic goals (Berland et al., 2015). Therefore, it would be more productive to understand how “science as
practices for students” (Manz, 2015, p. 118) emerge and function to achieve epistemic goals, rather than expecting communities of learners to adopt abstract disciplinary practices they have no connection to. From this perspective, this study contributes a detailed account of how a group of students engaged in and negotiated how to share and evaluate mechanistic models that explained their observations. Not only were students accountable to the community’s standards of reasoning and logic (epistemological), they were also accountable to the learning community in ways that have not been described by previous research (Erduran et al., 2004; Michaels et al., 2010, 2008; Osborne et al., 2004). Specifically, students were attentive to and modulated the affective valences of their contributions to mitigate any potential conflicts, while still debating the explanitory power of their mechanistic models.

This study also contributes to identifying and supporting disagreements in the K-5 science classroom. First, students in this study disagreed about each other's mechanistic models in ways that went beyond the overt opposition (e.g., “I disagree with...”) described in previous studies (Erduran et al., 2004; Michaels et al., 2010, 2008; J. Osborne et al., 2004). Therefore, it is important for educators to recognize how questions like, “Why wouldn’t there by any energy?” can highlight opposition, request information, and invite further discussion. As educators, we risk missing productive and rich talk about ideas and reasoning if we value only a few ways to enact disagreements. Moreover, expecting all classroom argumentation to follow predetermined structures and contain specific linguistic elements can limit how students develop a sense of and meaningfully engage in epistemic practices. Constraining what counts as a formal and productive disagreement may create conditions and expectations that could, inadvertently, alienate students from co-constructing knowledge. Therefore, it is important for educators to recognize and value the various discursive moves through which students can disagree with each other, rather than
following a prescribed approach. If a science learning environment requires disagreements that are more confrontational than the one analyzed in this article, for example, it would not be hard to imagine how students like Yesenia and Grace might have felt hesitant to participate.

Finally, reflecting on my role as the instructor in this exchange, I saw my main function as moderating the conversation and creating opportunities for students to meaningfully engage with each other’s ideas. I attempted to achieve this goal through a couple of different sets of strategies. First, I relied heavily on Talk Moves (Michaels & O’Connor, 2012; Michaels et al., 2010) in order to support students engage in Academically Productive Talk and listen to and engage with each other’s ideas. Additionally, I made a point to clarify for students any ideas or questions that may have seem lost on them, in an attempt to facilitate this type of engagement, as well as make the differences between the models concise, clear, and accessible. Despite these efforts, it was still hard to understand and follow the disagreement as it was unfolding. During the exchange, I realized that students were negotiating different models, but the complexity of the disagreement did not become as clear to me until I began the retrospective analysis as a researcher. Based on my journal entries, I assumed Yesenia was being very inquisitive and I was excited by that, but was also struck by the way her questions seemed to serve a purpose beyond requesting information. Towards the end of the exchange presented here, when Yesenia’s prosody changed and her exasperation became palpable, I began to realize that she might have been disagreeing with Toben and Grace all along. And yet, I still struggled to put my finger on how exactly she was challenging their explanatory model without explicitly saying so. In hindsight, it could have been productive for me, as the instructor, to highlight and celebrate the productive epistemic work students had engaged in, and point out how there were good reasons to support each model, but did not have sufficient evidence to discard one in favor of the other.
I offer this reflection on my practice and analysis as a recognition that identifying disagreements and unpacking their discursive complexity can be challenging, especially as they unfold. But if we avail ourselves of a more inclusive and finer-grained toolkit for identifying and making sense of disagreements as researchers and educators, we can take the necessary actions to leverage differences between explanatory models to support students meaningfully engage in epistemic practices and co-construct knowledge about the natural world.
CHAPTER 3

SUPPORTING ELEMENTARY-AGED STUDENTS TO PROBLEMATIZE ELECTRICAL RESISTANCE

By:

Enrique Suárez

To be submitted to: Journal of the Learning Sciences
Paper 2: part of a thesis submitted to the School of Education
INTRODUCTION

Research in science education has suggested that effective science learning environments provide students with the opportunity for engaging in the practices of science as an effective way for developing conceptual understanding (e.g., Duschl, 2008; Lehrer & Schauble, 2006a; Mann, 1912). This commitment to “science-as-practice” (Berland et al., 2015; Lehrer & Schauble, 2006b; Manz, 2015; Stroupe, 2014) is supported by a sociohistorical approach to learning that frames learning as the shift in participation through engaging in the practices of a disciplinary community (Lave & Wenger, 1991). Engle and Conant (2002) proposed that learning environments should provide opportunities for students to participate in productive disciplinary engagement: making contributions to knowledge building, spontaneously participating in knowledge-driven processes, and attending to each other’s thinking, through engaging in disciplinary work. Most science learning environments (K-12 or out-of-school time) seldom make these opportunities and resources available, particularly to students from non-dominant communities (Bevan, 2017; Rosebery et al., 2010; Vossoughi, Hooper, & Escudé, 2016).

Engle and Conant (2002) argued that productive disciplinary engagement was built on four main principles needed to be realized. First, instructors should encourage students to problematize content through posing questions and authoring proposals, rather than simply accepting facts. Second, environments need to give students authority to define and address problems, as well as become stakeholders in the process of co-constructing knowledge. Third, students should be held accountable to others and disciplinary norms, particularly by how their work is responsive to what community insiders and outsiders have established. Finally, it is necessary to provide relevant resources, intellectual and/or material, to support students in their sense-making (Engle & Conant, 2002). The realization of productive disciplinary engagement relies on the dynamic balance between all four principles, with some easily linked due to their
contributions to students’ sense-making. One line of research that needs further exploration is how the design and provision of resources can support students to problematize content: inadequate resources can make the problem insurmountable, while oversaturation can reduce the tasks’ complexity; both scenarios decrease students’ possibilities of participating in productive disciplinary engagement (Engle, 2011; Manz, 2015; Otero, 2004b; Varelas et al., 2008). Specifically, as science educators strive to design equitable learning environments, it is crucial to understand how design features can create opportunities for students from non-dominant communities to engage in disciplinary work. Moreover, it is key to further explore how the complexity and materiality of resources can create opportunities for these students to make sense of the natural world. Heeding the call, this study investigates what relevant resources can be introduced into the learning environment to support elementary-aged emerging bilingual students\(^3\) problematize natural phenomena and promote their participation in productive disciplinary engagement.

Several groups of researchers have explored how material resources can help create more equitable science learning environments. One example is Kafai, Peppler and collaborators investigations on how e-textiles can reframe gender-based participation in science and engineering (e.g., Kafai, Fields, & Searle, 2014; Kafai & Peppler, 2014). Another example is Brown and Ryoo’s computer program that change how academic language is introduced during science lessons for elementary school students who are learning English as a second language (Brown & Ryoo, 2008). Despite these efforts, making material resources available to students

\(^3\) These students are often referred to as English Language Learners (ELLs). In this paper, I build on the work of critical scholars (Escamilla & Hopewell, 2010; García, 2009b; Gutiérrez & Orellana, 2006) who propose the term “emerging bilingual students” to celebrate these students’ bilingualism, rather than privileging English, and highlight that they are learners of more than just English. It is important to recognize that these students represent multiple linguistic and cultural backgrounds, making them a heterogeneous group with varied resources and needs.
from non-dominant communities is not sufficient for disrupting preconceived notions of how these students co-construct knowledge about the natural world (Vossoughi, Escudé, Kong, & Hooper, 2013; Vossoughi et al., 2016). Specific to emerging bilingual students, it is particularly relevant to ask how we can design learning environments in which tasks and tools can be brought to bear to support these students to participate in productive disciplinary engagement. The first step is to recognize emerging bilingual students’ conceptual, linguistic, and cultural resources as assets (Gutiérrez & Orellana, 2006; Rosebery et al., 2010; Warren et al., 2001). However, more research is needed on how these students engage with material resources when making sense of and discussion natural phenomena.

In this paper, I share the results of a design study whose goal was to create opportunities for emerging bilingual students to problematize electrical phenomena. My goal is to explore the variable success of distinct sets of tangible experimental tools in supporting students to problematize electrical resistance, within the context of specific tasks. In the first section of the paper, I will frame the affordances for learning through interacting with tangible objects from a socio-constructionist lens, attending to how material resources can make features of phenomena accessible and investigable. In the second section I will describe the study design, outlining the high-level conjecture that guided the design and analysis of the learning environment, and the tasks included in an out-of-school time (OST) science education program for emerging bilingual students. The third section of the paper will describe the how the specific tangible experimental tools, in combination with tasks students engaged in, supported students to problematize intensive and extensive properties of electrical resistance. In the final section of the paper I will discuss the affordances and constraints of the designed unit, particularly attending to the ways in which the tasks and the experimental tools helped students develop a more nuanced
understanding of electrical resistance. This last section will also detail future changes to the conjectures that guided the design, their associated embodiments, and the unit.

**LEVERAGING TOOLS FOR INVESTIGATING NATURAL PHENOMENA**

Material resources and other tools have been an important aspect of how science educators create the means for supporting students’ conceptual understanding and development of disciplinary practices (Goldberg, Otero, & Robinson, 2010). Material resources are ubiquitous across science learning environments, and have been a staple in the physical science classroom for over a century (Otero & Meltzer, 2016; A. Smith & Hall, 1902). Throughout history, material resources have taken different forms to fit the tasks students engage in and achieve learning goals. Some have thought of these resources as tangible objects students can build and modify to develop conceptual understanding, either in learning environments in which students participate in open exploration (e.g., Bevan, 2017; Bevan, Gutwill, Petrich, & Wilkinson, 2015; Petrich, Wilkinson, & Bevan, 2013; Resnick, Berg, & Eisenberg, 2000) or learning environments with specific activities for students to engage in (e.g., Kafai et al., 2014; Papert, 1980; Peppler & Glosson, 2013; Resnick et al., 2000). Others have designed computer software that support students to learn key concepts and develop forms of epistemic practices (e.g., Bell & Linn, 2000; Brown & Ryoo, 2008; Otero, 2004b; Reiser, 2004), and others have thought of resources as tools for scaffolding desired modes of participation within learning communities (e.g., Otero, 2004b; Palinscar, 1998; Palincsar, Magnusson, Marano, Ford, & Brown, 1998).

All of these strategies build on the work of Lev Vygotsky (1978, 1980), who conceptualized learning and development as processes driven by the interactions of individuals with other humans, a community, and the set of cultural practices they represent. These interactions are mediated by tools, the sociohistorical artifacts present in their social and physical context. Specifically, these tools are invented and used by humans “as auxiliary means of solving a given
psychological problem (to remember, compare something, report, choose, and so on)” and performe the same function as any other tool for labor (Vygotsky, 1978, p. 52). Whether we use language or a light bulb, material and/or psychological tools have profound effects on how we interact with and make sense of our world. And while the tools we interact with help mediate our actions and thoughts, each tool has affordances, constraints, and unintended effects that are associated with the tasks they are being used for. Relatedly, Cole and Wertsch argue that “there is no tool that is adequate to all tasks” (Cole & Wertsch, 1996, p. 252), asking us to be intentional about the tools we choose.

Vygotsky also framed learning as a process of enculturation into a community, in which learners became aware of, experienced, and ultimately participated in the social and epistemic practices of that community. From this perspective, sociohistorical tools play an important role in the process of enculturation, particularly through mediating the learner’s knowledge and experiences with those of the target community, facilitating the engagement in practices of the target community. An example of such a target community is the science professional community, which adheres to disciplinary practices agreed upon by the community for investigating and co-constructing knowledge about the natural world. Material resources, such as graphical representations and lab devices, are essential because they mediate scientists’ engagement in disciplinary practices and sense-making. Therefore, tools that can support students to problematize physical phenomena are, by their very nature, creating possibilities for students to engage in the disciplinary practices of the science professional community.

Seymour Papert built on Vygotsky’s ideas and proposed that interacting with tangible objects can support children’s learning in science and mathematics (Harel & Papert, 1990; Papert, 1980; Papert & Harel, 1991). Papert believed that our learning environments, and society
in general, lacked the kinds of material resources upon which “more advanced intellectual structures” could be built (Papert, 1980, p. 20). To address this gap, Papert and Harel proposed constructionism as a theory for understanding how students can become active participants and drive their own learning through physically interacting with objects that represent phenomena and interesting problems (Papert & Harel, 1991). From a constructionist perspective, learning environments should support students to problematize content, and develop and represent their conceptual understanding, through designing, building, and/or modifying physical objects. For example, Papert introduced the Turtle as an object that students could control through writing code in LOGO and, in the process, learn about mathematics and graphical representations.

Papert’s constructionism has been the cornerstone for designing multiple kinds of learning environments, all of which offer opportunities for learners to build and interact physical material resources (e.g., assembling and programming robots) with the intent of addressing a problem they care about. It is through these interactions with material resources that learners have an opportunity to problematize content, posing questions about the natural world, making sense of phenomena relevant to the problem and represent their understanding in the final design. Making and tinkering spaces are one example of learning environments that follow these principles, allowing learners of all ages to design and construct physical artifacts to address a problem they are interested in (e.g., Bevan, 2017; Bevan et al., 2015; Vossoughi et al., 2013, 2016). However, understanding that tangible experimental tools (i.e., mediating artifacts) pose both affordances and constraints for problematizing content, it is important for designers of resources and learning environments to consider the tools’ features in relation to supporting students to raise problems, ask questions, and offer explanations about phenomena (Otero, 2004a; Peppler & Danish, 2013).
When designing and selecting material resources, it is crucial to evaluate the extent to which these tools support students to problematize content through making visible key processes and concepts related to the natural phenomena being considered. One recurring limitation of the kind of material resources used for supporting science learning is that they can function as “black boxes”, obscuring the inner workings and/or mechanisms that give rise to the phenomena that students observe and investigate (Kafai & Peppler, 2014; Resnick et al., 2000). In a paper outlining the reflexive role of tools for generating scientific knowledge and questions, Resnick and his collaborators (Resnick et al., 2000) proposed that instruments can support scientists to problematize the natural world. Understanding the affordances of experimental apparatuses, Resnick et al. propose that tools that support problematizing the natural world should be transparent by making its inner workings “easily seen and understood” (2000, p. 16), rather than opaque black boxes that hide fundamental processes and make them inaccessible and unintelligible. For example, Resnick and his colleagues observed how a fifth grader learned about Newtonian dynamics through building and refining a kinematic sculpture, changing the ramps’ angle of inclination until finding the one that would launch the marbles the farthest. Observing the effects of modifying the sculpture’s attributes on the launching of the marbles made visible the relationship between the grade of an incline and acceleration.

Similarly, Kafai and her colleagues (Kafai et al., 2014; Kafai & Peppler, 2014) built on the construct of transparency to design learning activities for students from non-dominant communities, creating opportunities for these students to build media through which to construct knowledge and tell their own stories. When designing learning environments, Kafai and her colleagues have made the complexity and messiness of the technology learners interacted with visible and accessible, leveraging the complexity to support the learners’ agency and their sense-
making. For example, Kafai and Peppler saw e-textiles as an opportunity for girls in out-of-school settings to experience and wrestle with the complexity of sewing with conductive thread on programmable LilyPads®. Through engaging in these activities, students learned key concepts about electrical circuits, such as polarity and shortcircuits, which students experienced when sewing circuits with uninsulated conductive thread that could be easily shorted (Peppler & Glosson, 2013).

Constructionism has explored how students’ interactions with and construction of tangible tools can support them in problematizing natural phenomena. Moreover, studies on how the transparency of experimental tools (i.e., making key concepts and processes accessible and intelligible) can support students’ learning and participation provide a strong foundation for designing opportunities for emerging bilingual students to investigate and learn about electrical phenomena. Transparency becomes an important construct for designing and/or selecting experimental tools that can support students to problematize electrical resistance through making key conceptual features visible and investigable. Informed by this research, this study explores the following specific research question:

1. How did the sequence of designed tasks, along with the distinct set of experimental tools, support a group of elementary-aged emerging bilingual students to problematize different conceptual aspects of electrical resistance?

**STUDY DESIGN**

Elementary-aged students’ understanding of electrical phenomena

Understanding how students make sense of electrical circuits has interested science education researchers for decades (e.g., R. Osborne, 1983; Peppler & Glosson, 2013). Roger Osborne reported that elementary-aged students usually proposed four models for explaining electrical current flow in a DC circuit: (a) unipolar – current runs only through one wire; (b) clashing
currents – current run through each wire and meet at the bulb; (c) less current or “used up” model – current runs through one wire, is used by the bulb, and less return through other wire; and (d) “same current” models (1983). Peppler and Glosson (2013) expanded on Osborne’s work, exploring students’ ideas about current flow, polarity, and connectivity, three crucial features in the functioning of circuits. Peppler and Glosson reported similar findings as Osborne with regards to students’ models of electric flow. Focusing on the material affordances of the equipment students investigated, and analyzing the students’ pre- and post-scores on a circuit diagram assessment, these authors found that circuits using conductive thread (e-textiles) supported students in moving towards canonical understandings of current flow, polarity, and connectivity. While these studies did not explore students’ ideas about electrical resistance, they provide a great foundation on students’ ideas about electricity flowing through conductive wires.

Little has been written about students’, specifically elementary-aged learners, understanding of electrical resistance. Most of the research on this phenomenon has focused on offering resources for supporting high school and college-aged students to learn about electrical resistance (e.g., Driver, Rushworth, Squires, & Wood-Robinson, 2005; Glynn, Britton, & Yeany, 2012; Mcdermott, Shaffer, & Constantinou, 2000). One study that focuses on students’ ideas (Engelhardt & Beichner, 2004) suggests that high school and college-aged “students did not understand that a resistor … has an inherent resistance based on its shape and the material from which it is made” (2004; p. 113). Research on elementary-aged students’ ideas about properties of matter could shed some light into how they conceptualize electrical resistance. Driver and her colleagues (Driver et al., 2000) reported that elementary-aged students struggled with the particulate nature of matter, specifically with grasping the concepts of atoms and electrons. This research suggests the nanoscopic scales of entities and phenomena can be counterintuitive for
elementary-aged students, given that it can be challenging to relate these concepts to everyday, macroscopic phenomena. Even Smith’s detailed learning progression on states of matter (C. L. Smith, Wiser, Anderson, & Krajcik, 2006) excluded any discussion about particulate nature of matter and atomic structure from the big ideas and learning performances for grades K through 5. Therefore, students could struggle to see electrical phenomena as dependent on the movement of free electrons, and electrical resistance as the likelihood that these electrons traverse and/or collide with particles from the crystalline lattice of the solid they flow through.

Common across K-5 science curricula and standards, electrical resistance is an important concept for students to experience and make sense of, particularly in relation to the transmission and transformation of electrical energy in a circuit. Since 1998, elementary school physical sciences standards have furthered emphasized the importance of understanding how energy is transformed and transmitted within a system. For instance, the Next Generation Science Standards (NGSS Lead States, 2013) suggests that fourth graders should have opportunities for answering questions like, “what is energy?” and “how is energy transferred?” Specifically, the NGSS proposes two performance expectations that guide students’ learning about energy: 4-PS3-2, which asks students to consider the transmission of energy by electrical current; and 4-PS3-4, which asks students to create a device, such as an electrical circuit, which can convert energy from one type to another. However, elementary-aged students have traditionally learned about electrical resistance in terms of conductors (e.g., metals) and insulators (e.g., non-metals), a binary distinction that implies that electrical energy can be either transmitted or not through a circuit, never regulated nor transformed (e.g., FOSS Kits). While initially productive, this heuristic does not explain, for example, why a lamp with a thinner filament shines dimmer than a lamp with a thicker filament, when connected to the same battery. Therefore, if our goal is for
elementary-aged students to explain and predict how energy is transmitted and transformed within electrical circuits, students need to engage in tasks that can support them to problematize electrical resistance in more nuanced ways. Moreover, these tasks need to include experimental tools that make visible for students how the resistors’ properties affect electric flow.

**Study context and participants**

This study took place in partnership with a local library system, working with elementary-aged emerging bilingual learners (predominantly from grades 3-5). Library administrators were excited and supportive of creating an out-of-school time (OST) science-based program for their younger patrons, especially one that would run for a sustained period of time and would serve emerging bilingual students. The program was offered three times throughout 2016 (Spring, Summer, Fall), at different library branches that serve predominantly immigrant families. For the purpose of this study, I will focus on the implementation at only one of the library branches: Dexter. This library branch serves a neighborhood of predominantly African-American and immigrant families from Latin America (e.g., Mexico), Sub-Saharan Africa (e.g., Ethiopia), and East Asia (e.g., Burma). During the summer 2016 iteration, the program recruited ten (10) students, spanning all elementary school grades; attendance fluctuated throughout the program and not all children were present at every session. All participating students were emerging bilingual and represented a wide range of home languages: from Spanish to Arabic to Somali.

Only four (4) of the students consented to participate in the research, and were present during the sessions I analyzed. These students were (pseudonyms): Yesenia, a Latina 4th grader, and her brother Elio who was in 2nd-grade; and Toben, a 4th-grade Nigerian-Japanese student, and his sister Grace, who also was in 2nd grade. All four students were emerging bilingual, and English became the program’s *lingua franca*; students still were encouraged to speak to each other in whichever language they felt comfortable in and thought was most useful. For most of the
program, Yesenia and Elio worked together on their experiments and explanations, and Toben and Grace worked together, as well. Eventually students would tire of working with their siblings, and requested pairing off with another student, or do the investigations individually.

**Design Decisions and Conjectures**

To address the driving research question, this study is based on a Design-Based Research (DBR) approach (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Sandoval, 2013; The Design-Based Research Collective, 2003). I chose DBR because of its affordances for systematically investigating the complexity of learning environments and developing learning theories. Specifically, this approach allowed me to explicitly state my conjectures about how the designed tasks and associated experimental tools could support emerging bilingual students to problematize electrical resistance, and then operationalize those conjectures into design features of the learning environment (Sandoval, 2013). Moreover, a design-based research method allowed me to formulate and refine localized theories about how emerging bilingual students in the program learned about electrical phenomena, and the means to support their learning.

Informed by research reviewed above, I generated one high-level conjecture that articulates how tangible experimental tools could support emerging bilingual students to problematize conceptual features of electrical resistance. Making this conjecture explicit *a priori* was important for understanding the learning that might occur in the program, describing the means to support it, and contributing to learning theory. The high-level conjecture and associated design features are described in the conjecture map (Sandoval, 2013) below (Figure 3.1).
Figure 3.1: Conjecture Map (Sandoval, 2013) that guided the study’s design and retrospective analysis.

The high-level conjecture that guided the study was: **Tasks that include specific tangible experimental tools can support students to problematize how intensive and extensive features of resistors affect electric flow through a circuit.** The literature on constructionism argues that creating, interacting, and/or investigating tangible tools can support students to problematize phenomena, especially if those tools make visible important conceptual aspects. Therefore, the study’s goal was to identify and articulate how distinct experimental tools, within the context of specific tasks, could support participating students to problematize conceptual aspects of electrical resistance. This high-level conjecture was mainly embodied through the designing different investigations for students to engage in that included distinct circuitry tools for each task. The program, which I will describe in more detail below, was designed to create opportunities for students to observe and investigate three major aspects of electrical resistance: electric flow through a circuit, obstructing electric flow, and changing properties of resistors to regulate electric flow. Moreover, the experimental tools that I brought to the learning
environment had to adhere to the principles of visibility, rather than making students investigate black boxes that revealed little about electrical phenomena. During early explorations of circuits and flow of electricity, students interacted with traditional materials used for building and testing circuits (e.g., batteries, bulbs, wires). These materials were chosen because of their ubiquity across elementary science classrooms and the potential familiarity students may already have had with them, increasing the ease for students to use them (Resnick & Rosenbaum, 2013). As I will detail below, traditional laboratory circuit tools supported students to investigate and explain how electricity flowed through a circuit. At the same time, due to their very nature, they provided limited possibilities for exploring electrical resistance given that these tools were designed for maximizing conductivity. For example, wires cannot be reshaped in order to increase or decrease their electrical resistance, therefore not revealing how the geometric properties of objects (e.g., width and length) affect how much electricity flows through them.

In order to further make visible extensive and intensive properties of electrical resistors, in addition to the traditional circuit tools, I incorporated into the investigation gel pens that use conductive and resistive ink, which function similarly to wires (Russo et al., 2011). Students drew lines of conductive ink, allowing them to build their own resistors by choosing the lines’ width and length and, therefore, changing the lines’ electrical resistance. For example, increasing or reducing the length of a line of conductive ink changes the electrical resistance of that line. Additionally, to give students authority in deciding how they would problematize the conductive lines’ resistance, I included multiple kinds of output modules for students to choose from when building their circuits (i.e., LED, buzzers, fans). The functioning of these modules depended on how electricity flowed through the circuit, which made them useful for externally representing the effects of electrical resistance on observable outcomes (e.g., spinning of a fan). All of these
modules provided students with helpful immediate feedback (Resnick et al., 2000; Resnick & Rosenbaum, 2013) on the effects of changing properties of resistors, and reducing or increasing the amount of electricity flowing through a circuit, can have on particular outcomes.

Finally, I designed and 3-D printed a plastic template (Figure 3.2) that could support students when drawing circuits with the CircuitScribe conductive ink, and when investigating how the lines’ width and length affected the flow of electricity through the circuit. The template included pairs of circular holes (Figure 3.2, A) that students could use when drawing the contact pads where to connect the modules; the distance between centers of these circles was equal to the length of the modules, taking away the need for students to measure the length of the module when drawing the contact pads. I included three vertical pairs of circular holes to support students when choosing the length of the circuit, without needing to lift and move the template. There also were two sizes of circular holes that gave students the option of choosing one when wanting to test how the size of the contact pad affected the functioning of the circuit.

![Figure 3.2: Design of the template students used when drawing and investigating circuits of conductive ink.](image)

Lastly, the template included two rectangular slots of different widths (Figure 3.2, B) that students could choose from when drawing the lines that connected the contact pads. Students used the template to alter the geometry of the conductive lines and observe how these changes affected the electric flow and, therefore, the functioning of the modules. For example, when
investigating the effect of changing conductive lines’ width, students could draw two circuits of the same length, by selecting the desired pairs of circles, but with different widths, by using the different rectangular slots, and observe how fast the fan’s blades spun on each circuit.

**Program Enactment and Tasks**

The design conjecture and related embodiments were implemented and tested through the *ElectroBuzz Science Program*, in which students investigated electrical phenomena and problematized electrical resistance. The program was structured in eight (8) sessions in which students engaged with different activities for investigating phenomena related to electrical resistance; each session lasted approximately sixty (60) minutes. Overall, the program was divided into three major parts, each of which had specific tangible experimental tools associated with them: investigating electric flow through a circuit, obstructing electric flow, and exploring the geometry of lines of conductive ink. These parts were designed and structured with the intention of creating a sequence of activities through which students could progressively problematize important conceptual aspects of electrical resistance. Despite the intentional planning of the program, an important commitment of the design was to attend to students’ own questions and interests about the phenomena they observed. This responsiveness was intended for giving students authority to problematize their observations of electrical phenomena and making them stakeholders in the investigations, rather than creating scenarios where students could act-as-if they were engaged (Engle, 2011). Therefore, I was committed to relating and grounding the sessions’ driving questions to students’ observations and own questions.

Each planned section of the program comprised sessions that were devoted to addressing specific questions related to aspects of electrical resistance, and included distinct set of tangible experimental tools to achieve those goals (see Table 3.1 for a summary of planned sessions, questions, and related tools). During the first session (Table 3.1, Planned, 1), students would
build circuits with traditional tools (e.g., battery, wires, lamps) and explain how they thought
electricity flowed through a circuit to light up a lamp; I had no requirements for what model of
electric flow students proposed. Once students had discussed electricity flowing from the battery,
through the wires, and into the lamp, in the second session (Table 3.1, Planned, 2) students
would explore how electricity could also flow through lines of conductive ink, rather than just
wires. This second session had two goals: students would to continue thinking about how
electricity flowed through a circuit, as they observed different modules being activated; begin to
consider what objects electricity could flow through, or not. Additionally, as students drew the
circuits freehanded or using the template, they would observe how changing the lines’ length
and/or width affected the functioning of the output modules. These observations would inform
future sessions (Table 3.1, Planned, 4 & 5), grounding the investigations in students’ questions.

Table 3.1: Planned sequence of activities, and enacted sequence of activities. (* indicates enacted
sessions/activities that had to be revisited due to fluctuation in attendance)

<table>
<thead>
<tr>
<th>Planned Sequence of Activities</th>
<th>Enacted Sequence of Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Session</strong></td>
<td><strong>Investigation</strong></td>
</tr>
<tr>
<td><strong>Title</strong></td>
<td><strong>Question</strong></td>
</tr>
<tr>
<td>1</td>
<td><strong>Building Circuits w/ cables</strong></td>
</tr>
<tr>
<td>2</td>
<td><strong>Drawing Circuits w/ ink</strong></td>
</tr>
<tr>
<td>3</td>
<td><strong>Does electricity flow through all objects?</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Drawing Circuits w/ ink</strong></td>
</tr>
</tbody>
</table>
### Exploring R of ink I – length
What happens if we make these lines very long?
Conductive ink, semiconductor modules; varying the lines’ length regulates electric flow.

**Building Circuits w/ cables**
How can we use batteries and wires to turn the lamp on?

### Exploring R of ink II – width
What happens if we make these lines very thick?
Conductive ink, semiconductor modules; varying the lines’ width regulates electric flow.

**Drawing Circuits w/ ink**
How is it that using this pen makes the lamp turn on?

### Exploring R of ink III – different inks
What happens if we draw these lines using other inks?
Conductive ink, semiconductor modules; varying the lines’ resistivity regulates electric flow.

**Does electricity flow through all objects?**
Could all objects make the lamp turn on?

### Final model of Resistance
Bring together how length, width, and different inks explain our observations

**Does electricity flow through all objects?**
Could all objects make the lamp turn on?

**Exploring R of ink I – length**
What happens if we make these lines very long?

**Exploring R of ink II – width**
What happens if we make these lines very thick?

During the third session (Table 3.1, Planned, 3), students would continue exploring whether all objects would conduct electricity, or if some could act as obstacles that would obstruct it. Students would draw a circuit with conductive ink with a gap where students could place common household items (e.g., screws, aluminum foil, cardboard, plastic) and test whether they acted as conductors or insulators. Students would choose and test eight objects, first predicting whether they would turn on the lamp or not, and then recording their observations in a table. Once they were done with their investigation, students would be asked to construct a rule for which kinds of objects allowed electricity to flow, and which ones did not, as well as explaining what was different between the two types of objects that caused the contrasting results. This
session’s goal was for students to begin problematizing how electricity could be stopped and, eventually, regulated (e.g., decreased), crucial for further understanding electrical resistance.

After establishing that some objects could obstruct the flow of electricity (i.e., intensive property), students would engage in a series of investigations that would create opportunities to problematize how the geometry of resistors (i.e., extensive properties) would affect electric flow. The first two sessions (Table 3.1, Planned, 4 & 5) would focus on exploring how the length and the width, respectively, of the lines of conductive ink affected how much electricity flowed through the circuit. Given that students were likely to have already identified these geometric variables as salient during Session 2 (*Drawing circuits w/ink*), the instructor would motivate the investigations by reminding them of their interest in exploring these questions. In case students had not spontaneously noticed these differences, I had planned to seed *extreme cases* in students’ investigations (Manz, 2015): suggest to one group to draw a very long circuit and connecting the lamp, suggest to another group to draw a very short circuit and connecting the lamp, and asking students to explain the difference in the lamp’s brightness. Both sessions would unfold very similarly: I would remind students of the geometric variable they were interested in testing, ask students to draw five circuits while changing that one variable and holding the other constant, compare the functioning of the output modules on each of those five circuits, and finally explain how that geometric variable affects the flow of electricity through the circuit. Students would then return to investigating the intensive properties of resistors, specifically by drawing circuits with inks of different conductivity and resistivity (Table 3.1, Planned, 6), observing how different inks would regulate electric flow, and conjecture what specifically about the ink could be affecting the functioning of the output modules.
The last two sessions of the program were designed with the intent for students to bring together their understanding of how intensive and extensive properties of resistors affected the flow of electricity through the circuit. Specifically, Session 7 (Table 3.1, Planned, 7) would be an opportunity for students to co-construct a model that would integrate how the conductive lines’ resistivity, length, and width, determined the functioning of the output modules and, therefore, electric flow. Finally, the design challenged (Table 3.1, Planned, 8) would give students an opportunity to apply their complete model of electrical resistance and construct a device that would solve a problem they would be interested in; an example could be drawing a very long circuit using inks of different resistivity in which the output modules would function the same no matter how far they are connected from the battery.

It is important to state that, while I had predetermined the driving questions for each session, I adjusted the pacing of the activities in order to accommodate fluctuations in attendance and students’ own questions. Once example of these changes was when Yesenia and Elio joined the program during Session 4, which made me decide to return to building circuits with traditional tools and explaining how electricity flows through them, giving them an opportunity to construct and share their model of electric flow. This meant leaving out other activities I had originally planned, like constructing a final model of electrical resistance and the design challenge. Besides revisiting investigations and questions, and removing others, there were no significant changes in how the sessions were enacted from how they were planned.

Each session followed general task and participant structures described in the conjecture map (see Figure 3.1). At the start of each session, the whole-group would begin with me – the instructor – prompting students to summarize the findings from the previous session as a way to lay the foundation for the question students would be investigating next. This framing time was
followed by a brief period during which students predicted answers to the question and possible experimental observations. Since I was not committed to students presenting canonical explanations about their observations, these periods were an opportunity for me and other students to listen attentively and understand each other’s reasoning. The second part of the session consisted of students working in small groups (2-3 students per group), proposing an investigation plan that would allow them to address the session’s driving question. My role was to support students as they decided on plan for collecting and interpreting data, asking questions and encouraging discussion amongst teammates. During the third and final stage of the session, in their small groups, students would construct explanations for their observations, often creating graphical representations of the entities and processes involved. Students would then share their explanations with the whole group and engaged with each other’s ideas, evaluating and refine them until reaching consensus on a common explanatory model; this was not always achieved. I facilitated these discussions through the use of Talk Moves (Michaels & O’Connor, 2012; Michaels et al., 2010): asking questions, highlighting students’ ideas, and encouraging students to share their reasoning.

Data collection
For this study, I collected data from two main streams: video and audio recordings of classroom interactions, and student-produced artifacts. I prioritized video data because it could yield the most information on how participating students interacted with the tangible experimental tools when investigating and discussing the electrical phenomena they observed. Video data was complemented by backup audio data recorded using a handheld audio recorder, in case the camera’s microphone was of low quality and made it difficult to understand students. The video data was collected using two video cameras and their positioning depended on the type of activity students engaged in. During the beginning of each session, when there was a
brief whole-group conversation about the session’s driving question, the camera remained stationary on a tripod and pointed towards the whole group (non-consenting students were excluded). This positioning of the camera was intended to capture students’ ideas and gesturing when interacting with other students. When students investigated different electrical phenomena in small groups, a camera was pointed towards each group’s work area. Cameras remained stationary on a tripod and pointed towards the center of the area where the groups of students were working. This angle was best for capturing how students used the tangible experimental tools when investigating electrical phenomena. Finally, during whole-group discussions at the end of each activity, students sat around the work table with the investigation materials within reach and other inscriptions they produced when sharing their explanations. The camera was positioned facing the students in order to capture their ideas. I panned and zoomed as needed, in order to capture how students used their representations to support the sharing of their reasoning.

In addition to video and audio recordings of the activities, I collected still images of work students produced while engaging in the investigations. I paid close attention to the inscriptions students produced for sharing their explanations, as well as the experimental setups they designed for collecting data to address the sessions’ driving questions (e.g., pieces of paper with lines of different lengths to investigate the effect of length). These student-produced artifacts helped me explore mechanistic models about electrical resistance students constructed, and understand what kind of thinking and talk students share via writing and/or drawing.

**Retrospective analysis**

Throughout the enactment of the program, I created implementation memos for each session, attending to the following features of implementation: the session’s learning goals; how the embodiments were supposed to support students to meet the activity’s learning goals; how students used the tangible tools each activity to problematize electrical resistance; and possible
differences between how the embodiments were planned and enacted, in order to inform future (re-)designs. These memos were instrumental for initial analyses on how the designed embodiments created the means for supporting students’ learning about electrical resistance. Therefore, the implementation memos later guided the selection of episodes for analysis.

After the program had ended, and all the data had been collected, the first step in the retrospective analysis was to strategically condense the data into manageable and accessible pieces (M. Miles et al., 2013) that could be revisited for finer-grained analysis. Specifically, I created content logs that summarized the video and audio recordings by dividing these data into 5-minute segments and describing students’ participation and communication in the investigation. The purpose of the content logs was to create a reduced data form that contained a coarse-grained analysis of the data and capture and highlight moments during the program in which the students’ participation addressed this study’s research questions. As part of the process of creating these access points into the data, I included analytical notes about how the students’ investigation and communication during any given 5-min segment addresses the intermediate outcomes outlined in the conjecture map (Figure 3.1) and three main research questions. These analytical notes focused on students’ observations and explanations about electrical phenomena and how the tangible experimental tools made properties of electrical resistance visible to students. To identify interesting episodes, I inspected the content log and analytical notes for entries described how students to problematized conceptual aspects of electrical resistance. Specifically, I included any video segment that contained at least one exchange between students, or between students and the instructor, which explicitly addressed any conceptual feature of electrical resistance (see Table 3.2 for summary). This choice excluded segments where there were no explicit mentions of these features, including working silently.
Table 3.2: List of 5-min segments that contained talk about conceptual features of electrical resistance. Some segments included videos from both cameras, particularly during small-group investigations, indicated below by which camera the data came from in parenthesis; no parenthesis means there was only one camera being used to capture the activity.

<table>
<thead>
<tr>
<th>Explaining Electric Flow</th>
<th>Obstructing Electric Flow</th>
<th>Geometry of Conductive Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Session 2</td>
<td>Seg10</td>
<td>---</td>
</tr>
<tr>
<td>Session 3</td>
<td>Seg5</td>
<td>Seg16 (cam1) Seg16 (cam2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seg19 (cam1) Seg22</td>
</tr>
<tr>
<td>Session 4</td>
<td>Seg2 Seg6 Seg8 Seg11 Seg13 Seg17</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seg11 (cam1) Seg12 (cam2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seg13 (cam1) Seg13 (cam2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seg14 (cam1) Seg11 (cam2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seg12 (cam1) Seg12 (cam2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seg13 (cam1) Seg13 (cam2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seg14 (cam1) Seg14 (cam1)</td>
</tr>
<tr>
<td>Session 5</td>
<td>---</td>
<td>Seg6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seg3 Seg4 Seg5 (cam1) Seg5 (cam2) Seg6 (cam1) Seg6 (cam2) Seg7 Seg8 Seg9 Seg10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seg1 Seg2 Seg3 Seg4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seg6 Seg7 Seg9 (cam1) Seg10 (cam1) Seg10 (cam2) Seg11 (cam1) Seg11 (cam2) Seg12 (cam1)</td>
</tr>
<tr>
<td>Session 7</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seg1 Seg3 Seg4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seg5 Seg6 Seg7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seg9 Seg10 Seg11 Seg12</td>
</tr>
</tbody>
</table>

The selected episodes were analyzed through coding, with each research question requiring a different set of codes. To understand how tangible experimental tools made visible properties of electrical resistance I inductively created first-cycle codes (M. Miles et al., 2013) that captured the properties of electrical resistance students alluded to when investigating electrical phenomena. For example, I created the in vivo code “length” to capture moments when students
referred to the length of the resistor (i.e., wire or line of conductive ink) as a salient feature that would affect the flow of electricity and/or functioning of the circuit. This set of first-cycle codes were then organized into second-cycle codes according to whether these features students were identifying were intensive (e.g., material) or extensive (e.g., width and length) properties of resistors. Additionally, since I was interested in capturing the full range of properties of electrical resistors students identified as salient for the functioning of the circuit, I added new inductive codes when students identified new properties of electrical resistors. See Table 3.3 for the first- and second-cycle codes related to features of electrical phenomena. The results from the coding allowed me to identify the exchanges in which students referred to different conceptual aspects of electrical resistance throughout the program. Moreover, to better understand how the experimental tools supported students to problematize electrical resistance, within the context of the tasks they were asked to engage in, I quantified the exchanges when students explicitly referred to conceptual features of electrical resistance.

Table 3.3: First- and second-cycle inductive codes on conceptual features of electrical resistance.

<table>
<thead>
<tr>
<th>First-Cycle Codes</th>
<th>Second-Cycle Codes</th>
<th>Sample of Coded Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Flow</td>
<td>Circular Motion</td>
<td>“If you put all the pieces together it makes a circle of motion of energy that runs through the wires, through the battery, and through the light bulb.”</td>
</tr>
<tr>
<td></td>
<td>Clashing Currents</td>
<td>“It (electricity) bounces off here ((points to both wires)) and it (electricity) goes ((tracing wires with fingers)) … it (electricity) goes all the way ((tracing wires with fingers) … over here ((touches lamp))”</td>
</tr>
<tr>
<td></td>
<td>Local / Section</td>
<td>“Energy can get go through the thick line”</td>
</tr>
<tr>
<td>Electrical Resistance</td>
<td>Passage</td>
<td>“Coz metal can go through and then it (electricity) can make it light up”</td>
</tr>
<tr>
<td></td>
<td>Obstacle</td>
<td>“The paper is making a roadblock”</td>
</tr>
<tr>
<td></td>
<td>Regulating</td>
<td>“Maybe because not all the energy can flow through and then it can’t reach the object.”</td>
</tr>
<tr>
<td>Material</td>
<td>Metal</td>
<td>“Metal can attract energy”</td>
</tr>
<tr>
<td></td>
<td>Non-Metal</td>
<td>“Cardboard has no iron”</td>
</tr>
<tr>
<td></td>
<td>Work</td>
<td>“Los que sirven (those that work) ((points to metal objects))”</td>
</tr>
<tr>
<td></td>
<td>Don’t Work</td>
<td>“Bubble wrap is not going to work because it has no iron”</td>
</tr>
<tr>
<td>Length</td>
<td>Small</td>
<td>“Because when I put a light right here, it was dimmer, and when I put a light right there it was lighter. So, I think that it depends on – if it’s short or long.”</td>
</tr>
<tr>
<td>--------</td>
<td>-------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Big</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>Thin</td>
<td>“Energy can get stuck on the thin line”</td>
</tr>
<tr>
<td></td>
<td>Thick</td>
<td>“If there is more space, the more energy goes through”</td>
</tr>
</tbody>
</table>

**FINDINGS**

In this section I identify and describe the ways tangible experimental tools supported students to problematize electrical resistance, within the context of the designed tasks. I first present a summary of the coding of the video data, highlighting the different conceptual features of electrical resistance students addressed throughout the program. Then I present an in-depth analysis of how the conceptual features became visible and relevant to students, as they engaged in the program’s activities and used distinct experimental tools.

**Summary of Coding Results: Supporting Students to Problematize Electrical Resistance**

To better understand how the experimental tools supported students to problematize electrical resistance, within the context of the tasks they were asked to engage in, I identified and quantified the exchanges between students, and between students and the instructor, that explicitly referred to conceptual features of electrical resistance (see Figure 3.3). For the sake of representational simplicity, I decided to collapse the first-cycle inductive codes *metal* and *non-metal* codes under the second-cycle code *material*. Students talked about how the tools they investigated behaved in relation to the flow of electricity: serving as passages, obstacles, or to regulate how much electricity flowed through the circuit. When students were asked to build circuits with traditional tools or conductive ink (sessions 2-5), students discussed the different conductive media (i.e., wires or ink) functioning as passages through which electricity could flow. Particularly, as Figure 3.3 shows through the occurrence of codes, students related the material composition of these media (e.g., metal) to their quality as passages. Additionally, when exploring the CircuitScribe output modules (sessions 3 & 5), students identified that paper
functioned as an obstacle that kept two components from fully making contact and, therefore, not allowing for electricity to flow. Finally, students also referred to the nature of the tools they were investigating as *passages* or *obstacles* when exploring whether common objects acted as conductors or insulators (sessions 6 & 7), again relating the material composition of the objects to their behavior, as shown by the co-occurrence of *material* and *passages/obstacles* codes. Students only considered the possibility that media could regulate how much electricity flowed through a circuit only when drawing and investigating circuits with conductive ink.

---

**Figure 3.3: Explicit mentions of conceptual features of electrical resistance during each session.** In Session 3 and Session 7, students began one investigation with one set of experimental tools and then switched to another investigation that involved using other tools.

In addition to addressing the tools’ behavior in relation to electric flow, students identified and mentioned properties of the tools they deemed salient when explaining their observations. First, when asked to problematize electric flow through a circuit using various experimental tools (sessions 2-5), students highlighted the material composition of the tools they used. Specifically, students most often addressed the metallic nature of the circuit elements and the conductive ink, as well as the non-metallic nature of the paper that acted as a roadblock between modules. Additionally, as Figure 3.3 shows, as students explored the conductive ink for the first time (session 3:ink & session 5:ink), students spontaneously attended to the width of the lines they
drew as salient features for explaining their observations of how the modules functioned. These observations of the effects of the lines’ width helped motivate the driving investigation questions for future sessions, as mentioned above. Second, when investigating whether common objects could obstruct electric flow (sessions 6-7), students identified the objects’ material composition as a salient feature for explaining their observations. While students had previously attended to material composition, Figure 3.3 shows a marked increase in the frequency with which students referred to material during these sessions. Finally, when students investigated the effects of the lines’ geometry on electric flow (sessions 7-8), students mentioned the length and width of the conductive lines significantly more often than they had before. Moreover, as Figure 3.3 shows, students’ mentions of the lines’ geometry co-occurred with regulating codes.

These results suggest that the tasks and tools students engaged in throughout the program supported them to problematize specific conceptual features of electrical resistance. Specifically, when investigating electric flow, students focused their attention on how the tools they used acted as passages for electricity, especially if they were made out of metal. After establishing that metals act as passages, students investigated the obstruction of electricity and focused their discussion on the material composition of the common objects they investigated (i.e., metal and non-metal). Finally, when returning to the question of how the lines’ geometry affected the functioning of the circuit, students identified the lines’ length and width as salient properties that regulated how much electricity flowed through the circuit. These results are an encouraging first step in testing the study’s guiding high-level conjecture. However, as I will describe below, experimental tools offered students different affordances for problematizing electrical resistance.

Experimental Tools’ Affordances for Problematizing Electrical Resistances

To better understand how experimental tools supported students to problematize electrical resistance, I analyzed how students used and interacted with the tools during the different tasks
of the program: investigating traditional circuit tools, testing insulators and conductors, and exploring the geometry of the lines of conductive ink. First, I present a summary of the different conceptual features of electrical resistance students explicitly mentioned as they interacted with the distinct experimental tools associated with each task (see Table 3.4). Specifically, I grouped all the mentions of conceptual features of electrical resistance according to the types of experimental tools students were using at that time, and quantified the codes’ frequencies. Students were more likely to talk about the circuit elements behaving as passages for the electricity when working with traditional circuit tools (e.g., wires). As Table 3.4 shows, students referred to wires as passages for electricity eight times, compared to only four times when using conductors and insulators, and two times when working with the conductive ink. However, when investigating whether common objects behaved as conductors or insulators, students were more likely to refer to the objects’ material composition, categorizing them according to whether they were made out of metal or not. Specifically, mentioned the material composition of the tool 33 times when working with conductors and insulators, compared to a total of 14 times total when using the other two types of materials (see Table 3.4). Finally, when students investigated the effects of the lines’ geometry, they mentioned the conductive lines’ length and width more often, and that the ink functioned to regulate the electric flow. These results suggest that specific experimental tools offered different affordances for supporting students to problematize aspects of electrical resistance. Specifically, the conductive ink seemed to allow students to identify and investigate how the geometry of resistors can decrease or increase electric flow, in ways that other tools could not, within the context of their specific tasks; this is reflected in the 54 instances in which students referred to the lines’ geometric properties when using the conductive
ink, compared to a total of four instances total when using the other two types of experimental tools. I explore these affordances in more depth below.

Table 3.4: Explicit mentions of conceptual features of electrical resistance when using specific experimental tools.

<table>
<thead>
<tr>
<th>Conceptual features of electrical resistance discussed</th>
<th>Specific Experimental Tools Used</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wires</td>
</tr>
<tr>
<td>Electrical Resistance</td>
<td></td>
</tr>
<tr>
<td>Passage</td>
<td>8</td>
</tr>
<tr>
<td>Obstacle</td>
<td>1</td>
</tr>
<tr>
<td>Regulating</td>
<td>0</td>
</tr>
<tr>
<td>Material</td>
<td></td>
</tr>
<tr>
<td>Metal</td>
<td>4</td>
</tr>
<tr>
<td>Non-Metal</td>
<td>1</td>
</tr>
<tr>
<td>Geometry</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>1</td>
</tr>
<tr>
<td>Width</td>
<td>1</td>
</tr>
</tbody>
</table>

Traditional Circuits Tools: Highlighting Flow of Electricity Through the Circuit

When building and investigating circuits with traditional circuit tools, the circuit’s conductivity was the most salient aspect of electrical resistance that became visible to students. Specifically, when the instructor told students “the goal of the activity to make the lamp turn on” and asked them to consider “why is the lamp turning on?” (Session 2), they built circuits, connected different lamps, and explained their observations by conceptualizing the wires as passages for electricity, highlighting the wires’ metallic nature. For example, when describing why a lamp he connected lit up, Toben stated⁴:

Excerpt 1:

The energy comes through the wires ((touches one of the wires)) and then you put on the metal things (alligator clamps) and it would go right here ((touches where the wire is clamped to the lead of the lamp holder)) and then into there ((touches where lead of the lamp holder and lamp meet)) and the light bulb would…

(Session 3: Revisiting wired circuits)

---

⁴ Transcription conventions: [] overlap; - self interruption; … pause; ( ) deictic terms; (( )) gestures; other punctuation added for increasing readability.
In his explanation, Toben mapped out the path through which the energy\(^5\) flowed, identifying and touching the different circuit elements along the way. Toben focused on the section of the circuit where the wires, the lamp holder, and the lamp came together, and narrated how the electricity moved from one to the next until lighting up the bulb. As he was tracing the electricity’s route through the circuit, Toben touched the wires, the connection between the wire and the lamp holder, and the connection between the lamp holder and the base of the lamp, bringing attention to these metallic junctions. And while not explicitly stated, I infer that Toben’s pointing to these parts of the circuit elements indicates that he thought the metal itself was an important feature to consider; he did not touch the plastic base of the lamp holder, or the plastic casing of the wires. These metallic parts of the circuit elements were exposed to the users, making them visible and salient for Toben to include in his explanation. Therefore, via his narrative and pointing, Toben presented an explanation for how electricity flowed through the circuit that included the material properties of the elements, properties he considered and observed through interacting with the tangible experimental tools.

Similarly, Yesenia shared a detailed account of how the electricity flowed through the circuit:

Excerpt 2:

All batteries ((touches the battery) have energy and the energy from the battery causes the whole thing to run ((moves hand in a circle above the complete circuit)) perfectly. Energy comes from a type of uh iron. So, that iron they put it in the battery and that makes energy. So, when the energy ((touches the battery)) hits the wire it goes through the wire ((runs hand along one wire)), through the metal ((points to the lead of the lamp holder)) because energy can run through metal. So, it runs through the metal and it reaches the light bulb and it causes the light bulb to light up.

(Session 4)

\(^5\) While it is sensible to assume that students meant “electricity” when saying “energy,” I will use the energy throughout this article to avoid erroneous assumptions about what students meant and honor their linguistic choice.
Yesenia’s narrative began with a claim about the battery having a special type of iron that generated the energy that would eventually enter and flow through the circuit. The energy would move through the wires and into the lamp, which Yesenia depicted by running her hand along the wire and then pointing to the metallic part of the lamp holder. As she summarized in the last sentence, Yesenia’s model narrated how the energy moved from the battery to the lamp, through the wires and through the circuit elements. As she described how the energy moved through the circuit, Yesenia also attended to the elements of the circuit she thought were relevant for her explanation. Not only did she think that it was a metal inside the battery that produced energy, but she also pointed to the metallic part of the circuit while saying, “energy can run through metal.” Just as in Toben’s explanation, the metallic parts of the circuit became relevant to Yesenia as she interacted with the circuit, and she eventually included their conductive nature in her explanation. Later in this session Yesenia added that “the metal can attract energy” (Session 4), bolstering her previous claim and the importance of the properties of metal for energy flow.

Both examples illustrate how investigating circuits while using traditional tools supported students to articulate how energy flowed through circuits, which included metal as an important feature. Yesenia and Toben agreed that the energy would move freely through the wires, reaching each of the constitutive elements of the circuit, and eventually reaching the lamp and turning it on. Moreover, both students attended to and accounted for the metallic nature of the different circuit elements through which electricity flowed (see Figure 3.3 and Table 3.4). Toben pointed to the metal parts of each circuit element he thought facilitated the transmission of energy. Yesenia stated that metal allows energy to flow, and that metal can attract energy. For these students, the conductive qualities of metal became visible and salient as they built successful circuits and explained how electricity flowed through them.
While investigating the flow of electricity with traditional circuit materials, students seldom attended to what could keep electricity from flowing through the circuit and lighting up the lamp. There was only one instance in which a student, Yesenia, spontaneously observed the thickness of the filaments of two lamps that shone with different brightness, and attributed the difference in brightness to the filaments’ width (Session 4). Other than this occasion, traditional circuit tools hid their resistive qualities from students, while the conductive qualities of metals were highlighted. This is not surprising, given that traditional circuit tools have been designed to increase their electrical conductivity, while decreasing their resistance. Therefore, while these traditional circuit tools supported students in thinking about metals’ conductivity, their (unintentional) black-boxing of resistivity could limit students’ possibilities for problematizing electrical resistance, especially if tasks are not intentionally designed to do so, like in this case.

Testing Conductors and Insulators: Considering What Could Obstruct Electricity

Students began developing ideas about electrical resistance as they investigated whether common objects (e.g., coin, cardboard, plastic, screw) acted as conductors or insulators, when replacing a section of a drawn circuit. The instructor introduced the task by stating, “I brought a bunch of thing to test, to see if they work, to see if they complete the circuit” (Session 6). These objects were intentionally chosen because of their capabilities for highlighting how objects can act as obstacles for electricity. As students examined the objects closely, they observed and described the material composition of the objects, and eventually relied on their assessment of the objects’ makeup for predicting and explaining their observations. Before testing the objects, students predicted which ones would complete the circuit and turn on the LED, based on the objects’ physical appearances. For instance, as soon students were presented with the objects, Yesenia grabbed the aluminum foil and claimed it would “work because it has a lot of iron” (Session 6), highlighting its metallic appearance. Elio also claimed that the piece of cardboard
would not turn on the LED, to which Yesenia added “cardboard has no iron” (Session 6). Yesenia and Elio’s remarks resulted in a classification system for which objects would complete the circuit, based on the objects’ material composition (i.e., metal or non-metal). Similarly, Toben predicted that “metal completes” (Session 7), adding, “coz metal can go through and then it (electricity) can make it (LED) light up … wooden and cloth doesn’t … coz it (wood/cloth) doesn’t send the electrons to through it (wood/cloth) and make it (LED) light up” (Session 7). The classification systems Yesenia, Elio, and Toben proposed were consistent with previous statements that metals allowed energy to move through the circuit (see Excerpts 1 and 2), a property that was made visible by the objects’ physical features they observed.

Students’ classifications systems were corroborated, and in some cases refined, as they investigated the objects’ effects on their circuits. Yesenia tested the metal screw first, smiling when she saw the LED turn on, and immediately said that she knew it would work because, “like I said before, metal and iron acts like wires” (Session 6). After she had tested all of the metallic-looking objects, she tested the non-metals, starting with a piece of hard plastic. Yesenia observed that the LED did not turn on with the plastic, and said “I knew it wasn’t gonna work because it has no metal or iron” (Session 6). Yesenia’s findings confirmed the original classification system, which distinguished between objects made out of metal and those that were not. Complementary to the material-based categories, Yesenia created a second classification system based on whether they completed the circuit or not: “los que sirven (the ones that work) y los que no (the ones that do not)” (Session 6). While the first set of categories highlights the objects’ material composition, (i.e., metal, non-metal), the second system considered her observations of which ones turned on the LED (i.e., it works, it does not work). The overlap of these two
classification systems indicates how material composition became visible for Yesenia as she investigated the objects, and salient enough to be included in her explanations.

Yesenia and Elio’s experiences show how investigating whether common objects behaved as conductors or insulators highlighted salient aspects to consider when predicting and explaining the objects’ effects on the circuit. As the task asked them to consider which objects would complete the circuit, Yesenia and Elio observed the external physical characteristics of the objects and created a priori classification systems for sorting the objects accordingly. Both students systematically tested and observed which object turned on the LED, or not, confirming their predictions and informing their explanations. Investigating which objects would complete the circuit created opportunities for Yesenia and Elio to see which kinds of materials allowed energy to move through the circuit (i.e., conductors), and which ones acted as obstacles (i.e., resistors), emphasizing the importance of considering the objects’ material composition in their explanations. This was a key first step towards conceptualizing electrical resistance as impeding and/or limiting the flow of electricity through a circuit, a stepping stone towards more nuanced understandings of how resistance affects the transmission and transformation of energy.

Within the context of asking students to investigate the behavior of common objects in electric circuits, the tools acted as black-boxes because students could not observe how changes to the objects’ intensive and extensive properties regulated the flow of electricity. These tools had associated constraints related to their physical nature; for instance, it would have been virtually impossible to modify the piece of cardboard in order to significantly reduce its electrical resistance and allow some electricity to flow through the circuit. However, the task could have been designed differently in order to create opportunities for students to problematize electrical
resistance. Perhaps students could have cut strips of aluminum foil of various length and width to create resistors with different resistances, making extensive properties visible and investigable.

Nevertheless, the insulator/conductor binary can leave students with only two conceptual options for predicting and explaining how electricity will behave in a circuit: it moves through (conductors), or it stops (insulators). These two options do not capture the possibility for only a small amount of electricity enters the circuit, or that some electrical energy could be transformed into heat due to collisions with nanoscopic particles. Therefore, if our goal is for students to develop a conceptual understanding of how energy can be transmitted and transformed in electric circuits, we need to create opportunities for students to experience and problematize the different properties of resistors that determined their electrical resistance. Designing tasks that include traditional circuit tools, and common insulators and conductors, would require a great deal of resources and ingenuity. Instead, I designed tasks that asked students to investigate new tools that could make extensive properties easily accessible when problematizing electrical resistance.

**Geometry of the Lines of Conductive Ink: Framing Resistance as Regulating Electric Flow**

Finally, students investigated and observed how the geometry of the lines of conductive ink affected electric flow, as they drew and completed circuits with different characteristics. The instructor introduced the task by showing students the CircuitScribe conductive pen and modules, and asked students to “figure out a way that you – using this pen and this special ink you can make these (modules) work” (Session 3); another way the instructor introduced the activity was through stating that a “way of connecting (modules) is by drawing with the pen on the paper and then figuring out how we can draw it to make the connections” (Session 5). As students were becoming familiarized with the CircuitScribe tools, they focused their attention on the conductive ink’s metallic appearance, and anticipated why this ink was different from others. For instance, after seeing the instructor draw lines with the CircuitScribe pen, Yesenia claimed
that the “ink has iron in it, or metal, so the metal or iron kind of acts like a wire” (Session 5). This statement indicates that Yesenia thought the conductive ink had similar material composition as the wires (i.e., intensive property) in order for the LED to turn on at the other end of the circuit. Yesenia tested and confirmed their claim at a later meeting (Session 7), when she drew a circuit using a marker and observed that none of the output modules would turn on.

Yesenia was the first student to observe how the width of the lines affected the functioning of the circuit. Her first drawn circuit had very thin lines (i.e., high electrical resistance), and when she placed the fan at the other end of the circuit, Yesenia observed that the fan’s blades struggled to rotate. When the instructor asked for her reasoning, Yesenia spontaneously said, “there’s not enough electricity to make it go” (Session 5). Yesenia continued to explore the effects of the lines’ width through a second drawn circuit that emulated a wired circuit, and had a thick and a thin line. Yesenia reasoned that “the fat one (line) reacts like the black one (wire), and the thin one (line) reacts like the red one (wire)” (Session 5)⁶, using the thick slot on the drawing template for the former, and thin slot on the template for the latter (see Figure 3.2). Yesenia justified her choice of width by stating, “if there is more space, the more energy goes through” (Session 5), suggesting that she was thinking about how the line’s width could decrease electrical resistance and increase how much energy ran through the circuit. Yesenia’s statements marked another important milestone in the investigation of electrical resistance because it was the first time that any student talked about resistance in terms of limiting the amount of energy that moved through a circuit, rather than in the all-or-nothing terms of insulators and conductors.

⁶ During the previous session (Session 4), Toben and Yesenia speculated that each colored wire performed a different function in the circuit. However, during that session, Grace proved that all wires behaved the same, regardless of the color of their outer casing. It is possible, then, that when comparing the wired and drawn circuits, Yesenia might have been referring to each wire serving different functions that were not intrinsically linked to their colors; instead, the colors could have become an index for distinguishing between them.
While Yesenia attended to the line’s width, at the other side of the table, Elio observed how the line’s length also affected electric flow. Specifically, Elio added two lines to the sample circuit the instructor had drawn, one of which was very long. When Elio placed the buzzer at the other end of his extension, he did not hear noises coming from it, after which he claimed, “I think it’s so long that – and so thin that it doesn’t work. Let’s try to make it fatter” (Session 5). When the instructor asked Elio why he thought the lines’ length made a difference, he stated:

Excerpt 3:

I think that the energy – the energy goes over here ((tracing line with pen, from closer to battery to closer to ink circle)) but some of it – some of the energy stops and there’s like a few – few energy coming up over here. (Session 5)

After hearing that the buzzer had not turned on, and observing that the lines he drew were long and thin, Elio suspected longer lines would make it harder for the energy to reach the other end, gradually decreasing how much energy moved through until there would not be enough to turn on the module. In reality, Elio’s circuit did not work because he had not drawn a complete circuit, and there was a mismatch between the poles of the buzzer and the poles of the battery.

These brief initial experiences with the conductive lines illustrated for students how changing the extensive properties of resistors could affect the flow of energy, and informed their future investigations. During the penultimate meeting (Session 7), the instructor reminded students that Yesenia thought that “maybe there is something about the length of the line” (Session 7) to motivate the session’s investigation question: testing circuits of different lengths and determine how they affected the function of the modules. Students had the authority to decide how they would collect evidence to answer the session’s question, particularly by choosing how long their circuits would be and which modules to test. Yesenia and Toben worked together and began by drawing circuit of the length of the drawing template, and chose the thin slot for the width. They
tested the buzzer first, then the fan, and finally the LED, all of which worked. When the instructor asked them to describe how long the next test circuit would be, Toben suggested drawing a shorter circuit, but Yesenia began drawing a circuit that was twice the length of the first one (i.e., twice the template’ length), keeping the width the same (i.e., using the thin slot). As she was drawing the new circuit, the instructor asked Yesenia to share her ideas:

Excerpt 4:
It would be harder for the energy to move … because it goes really fast, like those lamps energy’s going through, and it would pause it (electricity) for a moment at first. You would have to wait a bit, half a second or something.

(Session 7)

Yesenia reasoned that longer conductive lines would make the energy lose speed as it traveled, taking it longer to reach the modules. Toben, on the other hand, thought that varying the length of the lines would not affect the outcome. Yesenia connected the fan at the other end of the longer circuit, but it did not spin, even after she tried to manually jump-start it by pushing the blades. After testing the fan, Yesenia tested the LED and buzzer, both of which worked fine.

Before moving on, it is relevant to briefly highlight the role the drawing template played in supporting Yesenia and Toben to problematize the length of the conductive line. In their attempts to determine whether and how the lines’ length affected electric flow, Yesenia and Toben used to drawing template to hold constant a specific width, which corresponded to the thin slot on the template. This choice, in effect, allowed them to isolate the lines’ length as the only variable to investigate during this time. Additionally, Yesenia defined the full drawing template as one unit of length, which she then doubled when testing the effects of increasing the lines’ length. In this way, the drawing template allowed Yesenia and Toben to systematically and somewhat precisely vary the length of the circuits they would be testing. Therefore, the 3D printed drawing template
also acted as a material resource that supported Yesenia and Toben problematize electrical resistance, through allowing them to hold variables and vary others, and observe the effects.

The instructor asked Yesenia and Toben about the incandescent lamp, wondering whether it would shine with the same brightness on both circuits. Yesenia placed it on the shorter circuit, then on the longer circuit, and made the following remarks:

Excerpt 5:

1 Yesenia: It (lamp) looks bigger on this one ((points to short circuit)) than this one ((points to long circuit)).
2 Instructor: Toben, do you see what Yesenia’s doing? 

*(Yesenia moves the lamp again between the long and short circuit)*
3 Instructor: So, when Yesenia puts it (lamp) on this one ((points to short circuit)), it (lamp) turns on like that *(bright, lights up quickly).*
4 Instructor: What about if you [put it on this one ((points to long circuit))?
5 Yesenia: [really fast.
6 Yesenia: This one ((points to short circuit)) goes really fast.
7 Yesenia: And this one ((points to long circuit)) … *(dim, lights up slowly)* it (electricity) goes kinda slow.

*(The instructor goes to check on Elio and Grace who needed help)*
8 Instructor: So, what do you think is happening? How come the light bulb is not as bright on the longer one? What could be happening there?
9 Yesenia: Maybe because it takes lon – like I said, it takes longer for the big one – it takes longer for the energy to move toward the lamp.

*(Session 7)*

Yesenia began by comparing the brightness of the lamp when connecting it to either circuit, asserting that the lamp looked “bigger” (i.e., brighter) on the shorter circuit than it did on the longer one. Her observations were sensible because, holding the lines’ constant, the shorter circuit would have a smaller electrical resistance than the longer circuit. In addition to attending to the brightness of the lamp, Yesenia observed the speed with which the lamp turned on when placed on each circuit. Specifically, Yesenia noticed that the lamp reached its peak brightness on the shorter circuit slightly faster than it did on the longer circuit, leading her to conclude that the speed with which the electricity ran through each circuit was not the same. Toben and Yesenia included this observation in their reasoning when sharing their findings with Elio and Grace:
Excerpt 6:

1 Toben: The long one be slower to turn the light bulb.
2 Yesenia: What Toben was trying to explain is that when we try a small one (shorter circuit), and then a big one (longer circuit), and – what we thought was when we put the battery here ((points to one end of longer circuit)) and the light here ((points to other end of longer circuit)), we discovered that it takes longer and longer for the light to turn on because it’s a long way for the electricity to flow. And in the short one (circuit), when we did, it (electricity) was faster than this ((points to longer circuit)).

(Session 7)

In this excerpt, Yesenia compared the apparent speed with which electricity flowed through each circuit, and attributed the delay to the difference between the circuits’ length. Yesenia’s model could be generalized as follows: the longer the length of the conductive line, the longer the distance the electricity has to travel, and the longer it will take to reach the module, affecting both the brightness and the speed with which the lamp turns on.

The last session (Session 8) began with the instructor stating that there was only one question left to investigate, to which Yesenia and Elio responded that the question that remained unanswered was whether the width of the lines affected the functioning of the circuit. Yesenia did not think it would, while Elio did think width made a difference. When the instructor asked them how they would investigate the question, Elio suggested making “it (conductive line) as fat or as thin as you want” (Session 8). Following her brother’s advice, Yesenia used the drawing template to draw a circuit the length of the template with what she called “super fat” lines, using the widest slot available. She tested the fan first, which would not start unless she manually jump-started it by pushing its blades; Yesenia then tried the LED and buzzer, all of which worked. Once again, we see how the drawing template allowed Yesenia to make choices about controlling the length and width of the lines, in order to assess how varying the width affected electric flow. As a final step, she connected the lamp she and observed that “it’s kind of dim” (Session 8), although she did not explain why that was the case. After exploring the first circuit,
the instructor asked Yesenia how thick the next one would be, and she drew a second circuit as long as the first one but using the thin slot on the drawing template. Yesenia tested the fan first and, again, she needed to jump-start it manually by pushing its blades. Quickly after, Yesenia replaced the fan with the lamp; after seeing it light up, she widened her eyes, scoffed, smiled, and then said that the lamp was “way dimmer” (Session 8). From her facial expression, Yesenia seemed surprised by her observations, which contradicted her prediction that the lines’ width would not make a difference on the flow of electricity.

Yesenia said she would draw and investigate one final circuit with a “fat one (line) first, and then a thin one (line)” (Session 8), similar to the one she drew in Session 5. The first module she tested on the mixed-width circuit was the buzzer, which blared normally, but the fan, which she connected second, did not spin. Immediately after, Yesenia tested the lamp and it did not turn on; she then connected the lamp to the battery module, on other side of the circuit, and it shone brightly. When the instructor asked Yesenia why she thought the lamp worked when connected to the battery, but not at the end of the mixed-width circuit, she stated:

Excerpt 7:

Because this one (thin line) – because this one is thicker and there can be electricity through there. Like, the electricity can go this way ((runs finger towards the battery)) or that way ((runs finger away from the battery)), but maybe the electricity could get stuck on this one (thin line) because it’s small and too tight. And, so, maybe it can’t go through here ((runs index along thin line towards battery)) all the way back (to the battery).

(Session 8)

In her explanation, Yesenia attended to how the lines’ geometry could regulate the amount of energy that flowed through the circuit. Specifically, Yesenia inferred that a thin conductive line would not have the necessary space for the energy to move through it without any interruptions, much like it did through thicker lines. Therefore, in the mixed circuit, the lamp would not turn on because not enough energy would be able to flow through the circuit due to the bottleneck
created by the thinner line. Yesenia’s account addressed how the lines’ thickness was responsible for determining how much energy would fit in and move through the conductive media, contradicting her initial prediction (i.e., width did not matter), and explaining why the lamp was “way dimmer” when connected to the circuit with the thin conductive lines.

Aware that students would not have an opportunity to bring the results from their investigations into a final, coherent model of electrical resistance, the instructor drew a very short circuit with very thin lines and asked Yesenia to investigate its behavior. Yesenia tested all output modules, and the only one that did not work was the lamp, prompting Yesenia to suspect it was because of the width. When the instructor asked her to predict what would happen if they widened the lines, Yesenia said, “it would be really really really easy for the electricity to flow because it’s just a really short way and it would be plenty space to go” (Session 8). In this account, Yesenia coordinated the effects of the lines’ width and length, predicting that increasing the former would give electricity more space to flow, and the decreasing the latter would decrease the distance over which it would need to travel and slow down. And when asked to sort the circuits from best to worst, Yesenia stated, “the worst one (circuit) would be long and skinny, and the best would be short and big – and, I mean, fat” (Session 8). Thus, Yesenia concluded that circuits with long and thin conductive lines make it harder for electricity to flow through, while circuits with short and wide conductive lines would make it easier. Her conclusions agree with the canonical understanding of electrical resistance because decreasing the length and increasing the width of a resistor also decreases the overall electrical resistance, and vice versa.

Through their interactions with the CircuitScribe tools, students had opportunities to problematize conceptual features of electrical resistance that been hidden during previous sessions. Specifically, students were asked to investigate how the lines’ length and width
regulated the amount of electricity that flowed through the circuit and, thus, determined whether the CircuitScribe modules worked. This was the first time students could vary the length and width of a conductor in ways that would make visible the effects of those changes on the functioning of the circuit. Through investigating the lines’ geometry and observing the effects of those changes immediately (e.g., drastic changes in the lamp’s brightness), the conductive ink supported students to problematize extensive properties of resistors (i.e., line’s length and width). Understanding how the shape of conductor or resistors affects how electrical energy is transmitted and transformed in a circuit is important for understanding electrical resistance.

**DISCUSSION AND IMPLICATIONS**

In this study, I identified and articulated the ways in which experimental tools supported students in their investigations and discussions about electrical phenomena, especially for problematizing electrical resistance. The first finding, as demonstrated through the summary of codes, is that the designed tasks and the experimental tools created opportunities for students to problematize multiple aspects of electrical resistance: flow of electricity, obstructing electricity, and how extensive properties of resistors regulated electric flow. Additionally, each type of tool introduced affordances and constraints for supporting students to problematize electrical resistance. The evidence suggests that the CircuitScribe conductive ink made visible important aspects of electrical resistance, specifically how changing the conductive lines’ length and width affected how much electricity flows through the circuit. To end, I reflect on the limitations of the study’s conjecture and implementation, and propose refinements.

**Affordances of the design for problematizing conceptual features of electrical resistance**

The nature and sequencing of the activities, in combination with the distinct experimental tools, created opportunities for students to problematize the complexity of electrical resistance. As the analysis demonstrates (see Figure 3.3), students were able to progressively and
sequentially attend to different conceptual aspects of electrical resistance throughout the length of the program. As they participated in these tasks, students interacted and investigated with experimental tools that made specific aspects of electrical resistance visible and salient. Based on their observations and interpretations, students articulated models that accounted for how intensive (e.g., material composition) and extensive (e.g., length and width) properties of resistors affected electric flow. Students’ initial models focused exclusively on the conductive nature of the circuit elements, then moved to consider what could obstruct the flow of electricity as an important stepping stone, and their final explanations accounted for how the geometry of the conductive lines affected the transmission of energy. This progression in students’ investigations and explanations of electrical resistance is encouraging because it shows how a carefully designed set of activities, with the appropriate material resources (e.g., experimental tools), can support students to problematize electrical resistance beyond the insulator/conductor binary. And while not all students had the opportunity to construct a final model of electrical resistance, Yesenia’s ranking of circuits from better to worst in terms of regulating electric flow indicate that students who engage in these kinds of investigations could bring into coordination multiple conceptual features of electrical resistance to predict and explain their observations. Of course, the ultimate goal is for students to build on their models of electrical resistance to make sense of how energy can be transmitted and/or transformed in electrical circuits.

In considering further the interrelationship between material resources and problematizing content (Engle, 2011; Engle & Conant, 2002), the various experimental tools I included in the program afforded me to design tasks that made visible the intended features of electrical resistance for students (see Table 3.4, and Table 3.5 for a summary). Overall, within the context of their respective tasks, the tangible experimental tools supported students to problematize and
discuss conceptual aspects of electrical resistance. Specifically, investigating traditional circuit tools emphasized the circuits’ conductivity, while the testing of insulators and conductors prompted students to think about what could obstruct electric flow, and the CircuitScribe conductive ink made the length and width of resistors visible for students. Moreover, the CircuitScribe conductive ink offered new ways in which students could problematize the extensive properties of resistors, investigating how changing the lines’ geometry affected the flow of electricity. Interacting with these tools was the first time students could systematically vary the length and width of a conductor in ways that would have visible effects on the functioning of the modules. However, the tasks were designed with the intention of leveraging affordances of distinct experimental tools for problematizing specific features of electrical resistance, and there is no telling how other tools could have served similar goals. For instance, when investigating electric flow with the traditional circuit tools, Yesenia surmised that the thickness of the lamps’ filament could affect their brightness. Despite the task not explicitly asking her to consider how the physical properties of the traditional tools could regulate electric flow, Yesenia was observant and astute enough to identify thickness as a salient extensive property of resistors. This example highlights the need to further understand the affordances and constraints of the tools for problematizing electrical resistance, separate from the tasks’ context.

Table 3.5: Affordances and constraints of tasks and tools for problematizing electrical resistance.

<table>
<thead>
<tr>
<th>Type of Tangible Experimental Tool</th>
<th>Tasks</th>
<th>Affordances</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional Circuit Tools</td>
<td>Building a successful circuit with wires, batteries, lamps.</td>
<td>Exploring electric flow and conductivity of metals.</td>
<td>Students did not have opportunity to investigate the resistance of traditional circuit tools.</td>
</tr>
<tr>
<td>Common Insulators &amp; Conductors</td>
<td>Substituting sections of a circuit with insulators (e.g., cardboard) and</td>
<td>Some objects allow electricity through, like metals. Some objects block</td>
<td>Students did not have an opportunity to investigate how altering the geometry of</td>
</tr>
<tr>
<td>CircuitScribe Conductive Ink</td>
<td>Drawing successful circuits with conductive ink, and determining how the lines’ length and width affected electric flow through the circuit.</td>
<td>Changing the length and width of the wire-like conductive lines regulates how much electricity flows through.</td>
<td>Students could not investigate the effects of intensive properties of resistors given that the ink’s resistivity could not be changed.</td>
</tr>
</tbody>
</table>

Finally, the drawing template served as another material resource that supported students to problematize the conceptual features of electrical resistance. Specifically, the drawing template presented students with choices for how long and/or wide they would draw the lines of conductive ink, affording them to keep one variable constant while changing the other one. For example, when problematizing the lines’ length, Yesenia and Toben chose the thinnest slot on the template (see Figure 3.2, B), and drew two circuits: one the length of the template, and another twice that long. These systematic and intentional variations to the length and width allowed students to observe the effects of changing the geometry of the conductive lines, which in turn could have made these conceptual features of electrical resistance even more salient.

**Refining the conjecture, associated embodiments, and program enactment**

The analysis and findings reported here provide a basis for revisiting and refining the study’s high-level conjecture, its associated embodiments, and some aspects of the programs’ enactment. The that guided the study and analysis was: *Tasks that include specific tangible experimental tools can support students to problematize how intensive and extensive features of resistors affect electric flow through a circuit.* Based on my analysis, I would like to propose a refinement to the conjecture and restate it as: *designed tasks and chosen experimental tools need to provide affordances for making visible different conceptual features of electrical resistance.* It is not
enough for tasks to include distinct experimental tools, but rather the tasks need to be designed and sequenced in order to maximize these tools’ affordances for supporting students investigate features of electrical resistance. Moreover, I would like to propose a second high-level conjecture based on the study’s results: some experimental tools are more likely to make it easier to design tasks that make visible conceptual features of electrical resistance for students to problematize than others. As the analysis shows, different types of experimental tools provided different affordances for investigating electrical resistance, with the CircuitScribe conductive ink and drawing template facilitating how students problematized a resistor’s extensive properties.

This change to the conjecture requires a refinement of its associated embodiments, specifically: Tools and Materials – Experimental materials need to support exploration. While it is important for tools to support students to explore electrical phenomena, it is also crucial that the tools students investigate with have the kind of output and resolution necessary for making visible conceptual features of electrical resistance. For example, the CircuitScribe semiconductor output modules (i.e., LED, buzzer, fan) did not have enough resolution to illustrate how small variations in a line’s length and width increased (or decreased) its electrical resistance. In fact, the LED and buzzer would turn on regardless of how thin or long students drew the conductive lines. This lack of resolution could explain why Toben erroneously predicted that increasing the circuit’s length would not affect how much electricity flowed through it. Therefore, based on this study’s findings, the “tools and materials” embodiment should be refined to state: experimental tools need to make clearly visible salient features for students and can be easily modifiable.

Additionally, in order to test the new conjecture about how some experimental tools could make it easier to design tasks for students to explore electrical resistance, it would be helpful to modify the program’s materials and task structures. Specifically, it will be important for each
session to include reflection sheets that prompt students to consider the various conceptual features of electrical resistance throughout every single activity. Based on the analysis presented here, it is difficult to ascertain whether the traditional circuit tools were ill-suited for supporting students to problematize extensive properties of resistors. Relatedly, the program’s task structures would need to include explicit directions for the instructor to focus students’ attention on the effects of intensive and extensive properties of resistors on electric flow, regardless of the experimental tools associated with each session.

Taking these refinements to the study’s conjectures and embodiments into account, I would implement a series of modifications during the next iteration of ElectroBuzz. First, in accordance to the new high-level conjecture and changes to its associated embodiments, I would make sure to create opportunities for students to problematize the various conceptual features of electrical resistance during each session of the program. While it may take a lot of resources and ingenuity, Yesenia’s conjecture that the thickness of the lamps’ filament affected their brightness could be taken as evidence that traditional circuit tools could also support students to investigate the how a resistor’s geometry could regulate electric flow. This modification to the program could yield data to help refine the study’s conjectures.

Second, I would revise how to introduce the CircuitScribe ink and modules to the program, and how students become familiarized with them. While not described in detail in this analysis, students struggled great deal when figuring out how they could use the conductive ink to draw a functioning circuit, without my guidance as the instructor. This unstructured approach was designed with the intent of allowing students to explore the conductive ink and modules, eventually coming to the realization that the ink functioned just as the wires they had used before. During both Session 3 and Session 5, students spent over 30 minutes of open-exploration
time with the CircuitScribe tools, and made very little progress in terms of how to use the ink; they were quick to understand how the modules worked, however, as they connected different modules to the battery directly. While I had expected that it would be intuitive to go from “connecting wires” to “drawing wires,” that was not the case, and it took me showing them how I would draw a circuit for them to successfully draw one themselves; even still, Yesenia and Toben were more dexterous at drawing circuits, while Grace and Elio continued to struggle throughout the program. One possible issue that may have complicated how students familiarized themselves with drawing circuits was that the act of drawing the circuits did not resemble the act of connecting circuits. Specifically, students would connect circuits using wires almost in a circular fashion: start at the battery, connect one side of the lamp with a wire, and then connect another wire from the other side of the lamp to the other side of the battery. When drawing circuits, however, students would draw two pairs of contact pads first at a certain distance (see Figure 3.2, A), then they would connect the top two pads with a line and the bottom two pads with another line (see Figure 3.2, B), and finally they would place the modules. While in the abstract connecting and drawing circuits are equivalent to each other, the actual physical processes differ significantly, which might have contributed to the confusion. To address this issue, I propose modifying the introductory activity as follows: (1) students would have about 10 minutes of unstructured time to explored both the ink and the modules; (2) after that time, I would demonstrate for students how to draw a circuit, following a circular path similar to that students used for connecting a wired circuit (i.e., from end of a module to the next and back); (3) I would ask students to draw their own circuits following my example, without using the drawing template; and (4) once students successfully draw a few circuits freehanded, I would introduce the drawing template as a tool for standardizing lengths and widths. This scaffolded approach
would still offer opportunities for students to have the authority to explore and problematize the CircuitScribe components, while still providing resources that could give them traction.

The third modification I would make is to structure the program to guarantee that students have an opportunity to draw and investigate circuits with conductive inks of different resistivity. While students were able to problematize the conductive lines’ length and width, the tasks and tools did not create opportunities for them to also investigate how the material composition of the ink regulated electric flow. Therefore, by the end of the program, students were not able to collect and interpret evidence that would let them conjecture how material composition could also regulate electric flow; the only experience they had had with material composition was specific to insulators and conductors, the former obstructing electricity and the latter behaving as passages. Finally, I would make sure to create the space and time for students to co-construct a final model of electrical resistance that brought into coordination their findings from all of their investigations. Creating this final model would be key for students to consolidate their understanding and for me, as the instructor, to assess the completeness of their explanations. Despite not being able to have a session dedicated to this activity in the iteration analyzed here, it is encouraging that, when prompted by the instructor, Yesenia predicted and explained how drawn circuits with mixed lengths and widths regulated the flow of electricity.

As a final note, I would like to address the opportunities these tasks and tools created for these emerging bilingual students to participate in productive disciplinary engagement. As Vossoughi and her collaborators have argued (Vossoughi et al., 2013, 2016), making material resources available to students from non-dominant communities is not sufficient for disrupting preconceived notions of how these students co-construct knowledge about the natural world. With the support of the tasks and tools, the emerging bilingual students who participated in the
program problematized key conceptual features of electrical resistance, a complex phenomenon that is seldom addressed in the elementary school curriculum. These students asked important questions about the phenomena they observed (e.g., how does the width of the line affect electric flow?), had the authority to plan and implement investigations for addressing those questions (e.g., “we can make the lines as fat or as thin as we want to”), and shared with the community evidence-based mechanistic models. Through the analysis presented here, my goal was to exemplify how the interaction between the program’s activities and experimental tools created opportunities for students to engage in science disciplinary practices in order to problematize the natural world, opportunities which, as many have reported (e.g., Barton, 2001; Bang et al., 2012; Johnson et al., 2011), are seldom available for students from underserved communities.
CHAPTER 4

ESTOY EXPLORANDO SCIENCE: TRANSLANGUAGING IN AN OUT-OF-SCHOOL SCIENCE PROGRAM FOR EMERGING BILINGUAL STUDENTS

By:

Enrique Suárez

To be submitted to: Science Education

Paper 3: part of a thesis submitted to the School of Education
INTRODUCTION AND PURPOSE

In our attempts to make science learning environments equitable and accessible to emerging bilingual students, it is important to consider how to create opportunities for inviting and leveraging these students’ discursive practices in the service of making sense of the natural world. Bi-/multilingual researchers and educators call for learning environments to become “translanguaging spaces” (Wei, 2011), where students draw from and leverage new and multiple modes for communicating ideas and which “language boundaries are not policed and in which students are encouraged to rely on their full bilingual repertoires” (Poza, 2016, p. 15). Specifically, translanguaging is defined as “the deployment of a speaker’s full linguistic repertoire without regard for watchful adherence to the socially and politically defined boundaries of named (and usually national and state) languages” (Otheguy et al., 2015, p. 281). Translanguaging offers a theoretical and pedagogical lens for understanding how emerging bilingual students leverage their full semiotic repertoires (Kusters, Spotti, Swanwick, & Tapio, 2017), which comprise linguistic (García, 2009a; García & Kleyn, 2016; Otheguy et al., 2015) and non-linguistic (Blackledge & Creese, 2017) resources, for making meaning of the world. A growing body of research shows that creating opportunities for students to engage in translanguaging supported their learning, ranging from elementary-aged students improving their literacy skills (Collins & Cioè-Peña, 2016; Kleyn & Yau, 2016; Martínez, 2010) to pre-service teachers learning another language (Makalela, 2015). This study is based on those findings.

While translanguaging has a decades-long tradition in sociolinguistics and bi-/multilingual education, it is relatively new to the field of science education. Thus far, researchers have

7 These students are often referred to as English Language Learners (ELLs). In this paper, I build on the work of critical scholars (Escamilla & Hopewell, 2010; García, 2009b; Gutiérrez & Orellana, 2006) who propose the term “emerging bilingual students” to celebrate these students’ bilingualism, rather than privileging English above other languages, and highlight that they are learners of more than just English.
predominantly focused on how elementary-aged emerging bilingual students engage in reading and writing about science content (Espinosa & Herrera, 2016; Poza, 2016; Stevenson, 2013, 2015). And while valuable, this research addresses only a narrow portion of the different epistemic practices students will engage in when making sense of the natural world. In fact, research in science education suggests that science learning is more effective when students engage in epistemic practices of the discipline (e.g., Ford, 2008; Ford & Forman, 2006; Lehrer & Schauble, 2006b; Manz, 2015), influencing current national educational policy (National Research Council, 2012) and standards, such as the Next Generation Science Standards (NGSS Lead States, 2013). The need to create opportunities for students to engage in science practices raises the issue that curricula and teachers must support emerging bilingual students engage in scientific practices through translanguaging. Research is needed across various science learning environments to develop a more nuanced understanding of how emerging bilingual students leverage linguistic and non-linguistic resources when making sense of the natural world, and to better understand the conditions that can support emerging bilingual students’ translanguaging.

Translanguaging could be a powerful construct for understanding how emerging bilingual students leverage multiple communicative resources when co-constructing knowledge about the natural world. Relying on both linguistic (e.g., named languages) and non-linguistic (e.g., gestures) resources, emerging bilingual students could effectively communicate their ideas and explanations about the natural phenomena they are observing and investigating. And yet, we know little about what translanguaging looks like for emerging bilingual students when engaging in disciplinary practices of sciences. The purpose of this study is to understand the translanguaging practices of a group of elementary-aged emerging bilingual students in an out-of-school science program, where they investigated electrical phenomena. Specifically, I seek to
identify and describe the translanguaging practices these students engaged in, using multiple communicative resources, and the contextual factors that seemed to support them.

The manuscript is structured as follows. First, I present a brief review of the “assets-oriented” literature on supporting emerging bilingual students in their learning of science, followed by a brief review of the research on leveraging semiotic repertoires when translanguaging. I then describe the study context and participants, as well as the process of collecting and analyzing the data. Third, I present findings that describe the translanguaging practices students engaged when sharing their ideas about electrical phenomena, drawing on communicative resources from their full semiotic repertoire. The findings further focus on the purposes students’ spontaneous translanguaging practices served, and the how instructor set specific linguistic expectations throughout the program. The manuscript ends with a discussion on how students used multiple communicative resources to engage in scientific practices, and implications for supporting translanguaging as a tool for making science learning environments equitable and inclusive.

**LEVERAGING COMMUNICATIVE RESOURCES FOR MAKING SENSE OF THE PHYSICAL WORLD**

In this section I review science education research that calls for the need to frame emerging bilingual students’ conceptual, linguistic, and cultural resources as assets for making sense of the natural world. Additionally, I review the research on *translanguaging* and its call for doing away with socially-constructed language classifications, and instead recognizing that emerging bilingual students move through the world using different aspects of their *linguistic repertoire*. Finally, I address the call for expanding our notion of emerging bilingual students’ repertoires to include other communicative resources (e.g., gestures), which researchers have shown to as essential as speech and text when communicating with others.
Emerging bilingual students learning science

A sociolinguistic framing of language offers a lens for valuing emerging bilingual students’ multifaceted discursive practices as assets for co-constructing knowledge. From this perspective, communicating is conceptualized as a complex socio-cultural-historical activity that people engage in with the purpose of sense-making (Gee, 2001; Gutiérrez, 2008; Vygotsky, 1986). Namely, a linguistic repertoire becomes a socially-constructed tool that mediates communication between people, and understanding of the social and natural world. An individual’s linguistic repertoire is composed of myriad communicative resources, which are deployed and learnt through interacting with other individuals (Otheguy et al., 2015). If the ultimate goal of language is for individuals to make sense of the world why are certain linguistic resources more valued than others? Scholars argue that to achieve this goal, learning environments should position students as active agents engaged in meaning-making, and create opportunities for them to develop their linguistic repertoires through deploying and learning communicative resources when engaging in complex activities (Razfar, Licon Khisty, & Chval, 2011). This conceptualization of language sits in contrast to a Second Language Acquisition approach, in which learners are passive recipients of ready-made linguistic structures.

Extending an “asset-based approach” to language to the science learning environments, researchers have emphasized the importance of recognizing emerging bilingual students’ knowledge and communicative repertoires as productive for developing conceptual understanding and scientific disciplinary practices. Warren and her colleagues (Warren et al., 2001) asserted that emerging bilingual students enter learning environments with “productive conceptual, metarepresentational, linguistic, experiential, and epistemological resources” (2001, p. 531) for advancing their understanding of scientific phenomena. Through analyzing case studies of LatinX and Haitian Creole students exploring science questions, Warren and her
collaborators observed how learners relied on everyday language and experiences when making sense of their observations. For example, these researchers observed how a Latino student, Emilio, designed an experiment to explore ants’ behavior through putting himself in the ants’ position and deciding how to test the darkness of the habitat as a variable. Additionally, these students shared their thinking through recruiting discourse patterns characteristic of the cultural communities they identified with. Rather than evaluating students’ performance based on the use of technical vocabulary and structure of arguments, these researchers identified distinctive discourse features used by emerging bilingual students when problematizing phenomena, supporting the construction of scientific knowledge. Similarly, Rosebery and collaborators (Rosebery et al., 2010) framed learning as “an activity in which heterogeneous meaning-making practices come into contact—explicitly and implicitly, intentionally and emergently—to generate new understandings” (2010, p. 324). Specifically, these authors used Bakhtin’s *heteroglossia*, the “varied ways of conceptualizing, representing, evaluating, and engaging the world in language” (2010, p. 325), for understanding how emerging bilinguals used discursive practices for making sense of the world. They observed that emerging bilingual students investigated heat transfers and constructed knowledge about the Second Law of Thermodynamics, such as why salt works better than sugar for making ice cream. Rosebery *et al.* concluded that “new meanings developed through the analytic work students did across the boundaries of everyday and scientific words” (2010, p. 351), which was possible because the learning environment allowed students to use multiple linguistic resources when investigating and making sense of physical phenomena. This research resembles a *resources* perspective on students’ understanding of the natural world, which proposes that students’ knowledge and experiences need to be leveraged in the service of building more sophisticated conceptual understanding (Elby & Hammer, 2010; Hammer, 2000;
By recognizing emerging bilingual students’ discursive practices as productive tools for making meaning, this tradition builds a bridge that connects students’ discursive practices to disciplinary practices for making sense of the natural world. Scholars in this tradition have tried to understand how emerging bilingual students’ discursive practices are productive for sense-making and resist deficit-oriented narratives constructed around these students (e.g., Lee & Fradd, 1998; Lee, Fradd, & Sutman, 1995). However, much research needs to be done in order to understand how exactly emerging bilingual students leverage a wide range of communicative resources when engaging in epistemic practices for making sense of the natural world. For example, it would be important to understand how bilingual students recruit multiple linguistic resources when sharing mechanistic models about physical phenomena.

Translanguaging through using *linguistic repertoires* when talking about the natural phenomena

The term *translanguaging* was first introduced into sociolinguistics and bi-/multilingual education by Cen Williams (García, 2009a), a Welsh educator concerned with how students navigated their heritage language (Welsh) and the language sanctioned by their schools (English). Since then, there have been multiple definitions of the construct, all of which have adapted to the sociohistorical and sociopolitical contexts in which it gets used. Thinking broadly about bi-/multilingual speakers, Otheguy, García, and Reid (Otheguy et al., 2015) define translanguaging as, “the deployment of a speaker’s full linguistic repertoire without regard for watchful adherence to the socially and politically defined boundaries of named (and usually national and state) languages” (2015, p. 281). This definition is grounded in the position that “named languages” (e.g., English, Spanish, Arabic) are socially and politically constructed, and cannot be differentiated on the basis of grammatical structures (Otheguy et al., 2015). Through rejecting socially constructed barriers between languages, translanguaging rejects a monoglossic
framing of bi-/multilingualism notion that these students have multiple separate whole languages that are kept separate and used independently. The *trans* prefix denotes the practice of transcending arbitrarily defined linguistic barriers and hierarchies (García & Kleyn, 2016), and leveraging different linguistic resources for communicative and meaning-making purposes. Finally, translanguaging conceptualizes “named languages” as conglomerates of lexical and structural resources that make up the *linguistic repertoires*, which bi-/multilingual speakers leverage when communicating and meaning-making.

Socially constructed language ideologies and policies, however, restrict students’ access to their full linguistic repertoire, often requiring bi-/multilingual students to use the dominant named language (García & Kleyn, 2016; Martínez, Hikida, & Durán, 2015; Otheguy et al., 2015). For example, states like Arizona, California, and Massachusetts restricted the use of heritage languages with emerging bilingual students and created English Immersion programs that focused solely on developing these students’ English fluency (Rumberger & Tran, 2010). Understanding the consequences of these restrictions on learning and participation, proponents of bi-/multilingual education call for learning environments to become “translanguaging spaces” (Wei, 2011) where students can use the full extent of their linguistic repertoire for creative and critical purposes. Specific to K-12 classrooms, García and Sylvan (García & Sylvan, 2011) describe translanguaging as, “the process by which bilingual students and teachers engage in complex discursive practices in order to ‘make sense’ of, and communicate in, multilingual classrooms” (2011, p. 389). Thus, translanguaging requires pedagogical practices that support students to leverage their full linguistic repertoires in the service of learning (García & Kleyn, 2016): (i) constructing collaborative and cooperative task structures; (ii) leveraging multilingual and multimodal learning materials; and (iii) enacting translanguaging pedagogical
practices that give bi-/multilingual students permission to “bring their language practices to the surface and into the open” for meaning-making (2016, p. 23).

Predominantly, research on students’ translanguaging has focused on developing learners’ literacy skills. For example, when investigating the translanguaging of 6th-grade LatinX students, Martínez (Martínez, 2010) observed that students engaged in sophisticated discursive practices through the use of “Spanglish.” Martínez uses the terms “Spanglish” and “Spanish-English code-switching” to denote the “dynamic hybrid language practice” (2010, p. 125) LatinX students engaged in, acknowledging that both terms are inadequate for capturing this linguistic complexity. Still, Martínez chooses to use Spanglish because this is the noun preferred by those who engage in this practice. Martínez observed that students adapted their use of Spanglish according to their perceived audience, such as using Spanish to address other students and using English when addressing adults. Moreover, students used Spanglish for communicating nuanced and subtle meanings, like when negotiating the racial hierarchies that exist in Spanish-speaking countries. These findings led Martínez to conclude that students’ translanguaging supported them to engage in discursive practices that resembled those that were expected from the state’s English Language Arts Content Standards, such as students’ writing exhibiting awareness of who their audience was. Similarly, Kleyn and Yau (Kleyn & Yau, 2016) observed how a group of 2nd-grade students moved fluidly between English and Spanish during an English Language Arts lesson. Specifically, these authors observed that students’ writing output increased when they were able to use both English and Spanish, suggesting that being able to access a broader set of linguistic resources supported their writing production. Finally, investigating how South African pre-service teachers learn Sepedi, Makalela (Makalela, 2015) observed that translanguaging supported these teachers’ language development. Using a randomized-control experiment
approach, Makalela assigned thirty pre-service teachers to the experimental group, for which the treatment allowed “used translanguaging strategies that emphasized flexible use of the target language, their different home languages and English” (2015, p. 206); thirty other teachers where randomly assigned to the control group, which was taught using Sepedi as the only language allowed in the learning environment. When comparing the two groups, Makalela found that pre-service teachers in the treatment group, on average, improved their recognition of Sepedi words by fifty points, while pre-service teachers in the control group only improved their scores by twenty-five points; these differences were statistically significant (p < 0.05). Pre-service teachers in the treatment group also experience a slightly higher increase in reading proficiency, on average, compared to pre-service teachers in the control group; these differences were not statistically significant. These findings led Makalela to conclude that creating translanguaging spaces was productive for supporting the pre-service teachers’ multilingualism.

While relatively new to the field of science education, some research has already been done to understand how elementary-aged emerging bilingual students engage in translanguaging practices in science learning environments. For instance, Poza (Poza, 2016) studied how LatinX emerging bilingual students in an elementary classroom engaged in translanguaging practices when learning about the periodic table of elements. Poza observed that students moved between websites in English and worksheets in Spanish when writing a report about the elements, as well as using nouns in English and Spanish when finding examples of elements in their surroundings. Based on these findings, Poza concluded that the emerging bilingual students he observed did not adhere to socially constructed barriers that separate English and Spanish, and instead drew from a broad linguistic repertoire when collaborating and learning content. Similarly, Espinosa and Herrera (Espinosa & Herrera, 2016) explored the translanguaging practices of LatinX
emerging bilingual 6th-graders when learning about states of matter. Encouraged by their teacher, Ms. Montoya, students used both English and Spanish during whole-class discussions about their observations, when writing notes that synthesized the information they read, and to learn academic vocabulary. Espinosa and Herrera concluded that Ms. Montoya made her science lessons a translanguaging space, where her students used multiple linguistic resources that were salient and productive when co-constructing knowledge about the states of matter.

Other studies have focused on science classrooms that restricted students’ use of their full linguistic repertoire, hampering the creation of translanguaging spaces. Stevenson (Stevenson, 2013, 2015) focused on how emerging bilingual students in an elementary school, which offered bilingual programs, used Spanish and English when learning science. Stevenson noted that the science classroom was characterized by an intentionally monoglossic approach to bilingualism (i.e., keeping Spanish and English separate), as the teacher required that students spoke English when engaging in the science activities. These studies’ main finding was that students used specific named languages according to the social context of the activity. Specifically, Stevenson found that students spoke English predominantly when interacting with the teacher, particularly during didactic activities, whereas students spoke Spanish predominantly when interacting with other students, particularly during laboratory activities. According to Stevenson (2015), this phenomenon could be attributed to speech accommodation, or the tendency of a speaker to match the speech of their interlocutor. Moreover, Stevenson (2013) found that emerging bilingual students used Spanish when organizing tasks, seeking clarification, and supporting others to complete schoolwork, while they used English when conveying science understanding, especially in written form. Stevenson concluded that, despite the restrictive language policies of the science classroom, students purposefully chose which named language to use when
participating in different forms of learning. Students’ purposeful accommodation of their interlocutor’s speech is interesting, although it raises questions about how transformative translanguaging was in that context. For translanguaging to be effective, equitable, and transformative the full extent of students’ linguistic repertoires must be equally valued and used for meaning making. Stevenson’s findings indicate that students used different linguistic resources for different purposes: Spanish predominantly for organizing the social world, while English predominantly for exploring the natural world. This distinction in how students used specific resources for specific purposes suggests that science learning environments can reify linguistic hierarchies, which keep emerging bilingual students from using their full linguistic repertoires when co-constructing knowledge about natural phenomena.

These studies offer a window into how emerging bilingual students leverage a wide range of linguistic resources (e.g., named languages) when learning science. These studies begin to suggest that creating opportunities for students’ translanguaging can support their participation in science activities. Despite their valuable contributions, these studies present a limitation associated with their context and content, as well as an analytical complication. First, the studies reviewed here focused solely on students engaging in translanguaging practices in the service of reading and writing about science, which represent a small portion of the different epistemic practices needed for making sense of the natural world. Therefore, further research is needed on how emerging bilingual students engage in translanguaging when, for example, presenting and evaluating mechanistic explanations of their observations; this study intends to address the gap. Secondly, while the studies reviewed here ascribe to a definition of translanguaging that critiques socially constructed barriers between named languages and a monoglossic perspective on bilingualism, their analyses focus on the moments when students switch between named
languages (predominantly English and Spanish). This analytical choice creates a tension difficult to navigate, given that distinguishing between named languages offers researchers with analytical traction, and yet their analyses reify the same socially constructed barriers that separate named languages. Moreover, the results from this research frame students’ flexible bilingualism as consecutive instances of code-switching (Martínez, 2010, 2014), transitioning between Spanish and English, for example. Inadvertently presenting speakers’ use of their semiotic repertoire as code-switching reduces the complexity and richness with which bi-/multilingual speakers communicate and engage with the world. To avoid these traps, we need to find analytical approaches that can help us leave behind the ubiquitous monoglossic perspective of bilingualism, especially when investigating students’ translanguaging practices. One possible solution is to continue to broaden our definition of what constitutes a productive resource for translanguaging, in an attempt to continue moving away from boundaries and hierarchies. Another productive avenue is to consider Spanglish, for example, as its own linguistic repertoire and sidestepping the trap of unintentionally maintain the same barriers we are trying to dismantle (Martínez, 2010, 2014; Martínez, Durán, & Hikida, 2017).

Translanguaging through leveraging semiotic repertoires for making sense of natural phenomena

Returning to the framing of communication as a complex socio-cultural-historical activity, sociolinguist and bilingual education researchers have recently called for including non-linguistic resources as part of the repertoires bi-/multilingual speakers draw from when translanguaging (Blackledge & Creese, 2017; Kusters et al., 2017). Human communication is possible due to their reliance on multiple modalities, spanning both linguistic and non-linguistic forms (C. Goodwin, 2000). Rather than being auxiliary, non-linguistic forms of communication, such as gestures, eye gaze, body positioning, have played an important role in supporting humans to communicate and make meaning of their world (Goldin-Meadow, 1999; D. McNeill, 1992).
Therefore, it is important to leave behind theoretical constructs and policies that value spoken and written communication over other forms of sharing, and for educators to welcome and leverage a variety of communicative resources that can support students to co-construct meaning.

Kusters and her collaborators (Kusters et al., 2017) argue that, while some research on translanguaging has emphasized a multimodal approach to communication, most studies continue to prioritize spoken and written forms over others. In an attempt to re-evaluate the hold of linguistic forms of communication over the construct of translanguaging, these authors champion efforts to blur the boundaries between linguistic and non-linguistic communicative resources. To this end, Kusters and her colleagues (2017) suggest the construct *semiotic repertoire* when thinking about translanguaging practices, in order to value linguistic and non-linguistic resources equally. Additionally, Kusters *et al.* (2017) recognize that relegating non-linguistic resources has created hierarchy of which semiotic resources are more prized than others. If the goal of translanguaging is to create opportunities for speakers to communicate through leveraging their full semiotic repertoires, these authors call for dismantling the power asymmetries that can restrict interlocutors’ access to all the resources that enrich communication.

Heeding the call for understanding how speakers rely on *semiotic repertoires* when translanguaging, Blackledge and Creese (Blackledge & Creese, 2017) focused specifically on the “corporeal dimension of translanguaging,” how speakers use their body when communicating (2017, p. 250). These authors recognize the importance of defining translanguaging as a process of selecting communicative resources from a broad semiotic repertoire, rather than being limited to only choosing between named languages; they argue that it is crucial that non-linguistic resources are included and valued as part of the repertoires speakers draw from, such as those associated with the body. Rather than separating the linguistic from the embodied, Blackledge
and Creese propose that interlocutors communicate and make meaning through integrating verbal and non-verbal action. Through ethnographic research, these authors identified and described how vendors and shoppers from different cultural backgrounds communicated with each other at a meat market, focusing their attention on the gestures, mimes, and hand signs interlocutors deployed. In one instance, Blackledge and Creese observed how a shopper said “pork” and then moved his hands close to each other to ask for a piece of pig’s small intestine; in response, the butcher pointed to his stomach and shook his head side to side to say they no longer carried small intestines. On another occasion, the researchers observed a Chinese woman ask for six pieces of offal through a hand sign in which “only her thumb and little finger are sticking out” (2017, p. 265), to which the English-speaking butchers responded with the word for “six” in Mandarin; the transaction was successful. Based on observations like these, Blackledge and Creese concluded that these individuals drew from multilingual and multimodal repertoires when engaging in translanguaging practices, making visible the complexity of communication between people with different histories. Thus, the researchers concluded that the body became an integral tool that supported translanguaging, as speakers used linguistic and non-linguistic resources from their full semiotic repertoire for interacting and making meaning.

Among the possible non-linguistic forms of communication students can rely on when sharing and engaging with ideas, gesturing is both common and powerful. The relationship between gestures, communication, and speech has been a contested one, with some researchers arguing that gestures become unnecessary and/or redundant once speech is fully developed, while others argue that gestures and language are intimately linked and are co-expressive (Radford, 2009; Radford, Edwards, & Arzarello, 2009). Specifically, McNeill suggests that gestures and speech occur simultaneously and, in fact, gestures that accompany speech present
similar semantic meanings and play similar pragmatic functions (D. McNeill, 1992). Goldin-Meadow (1999) argues that gestures can help speakers express ideas that may be challenging to communicate through speech, thus providing speakers with an additional representational system that can both reduce cognitive effort and serve as a tool for thinking. Sfard (2009) suggests that gestures can support effective communication by ensuring interlocutors are speaking about the same object, thus strengthening the symbolic and symbiotic relationship between gestures and speech. Because of these affordances, gestures should be considered as integral parts of speech, and communication in general, rather than redundant to talk; thus, gestures should not be analyzed in isolation from the communicative acts.

Acknowledging the wide range of gestures speakers could rely on to accompany their speech, and in order to understand the function gestures play in communication, McNeill and his collaborators (1992) investigated how individuals used gestures for conveying meaning. Specifically, McNeill developed a taxonomy of gestures to identify the kinds of gestures speakers rely on when engaging in different communicative acts (e.g., story structure vs. story events) and systematically infer what information these gestures communicated. McNeill defined four main dimensions of gesture after observing speakers of different agents and different heritage languages, each with particular body motions and functions. Deictic gestures are specific hand movements used in concrete or abstract pointing that derive their meaning from the context in which the interlocutors communicate; it can be challenging to disambiguate what the speaker means by a deictic gesture (e.g., “here”) without having access to the referred object. Iconic gestures are hand/arm movements that bear a transparent, perceptual relation to the semantic content of speech, and/or concrete entities and events the speaker is referring to. An example of an iconic gesture would be when a person says they need to write an academic article
and they move their fingers in a fashion that resembles typing on a keyboard. Metaphoric gestures refer to a visual image, much like iconic gestures, but this image is related to an abstract concept, like a thought or electricity. An example of a metaphoric gesture would be when a physicist holds their hands to resemble a sphere, fingers curved and palms facing each other, when talking about electron orbitals in the Bohr atomic model. Finally, Beats are a form of gesture used for providing temporal and/or emphatic structure to utterances, and yet their form does not present any distinguishable meaning.

Unfortunately, there is a dearth of research on how emerging bilingual students engage in translanguaging practices through gesturing when making sense of physical phenomena. As Blackledge and Creese point out, much of the research on multimodality has focused on monolingual speakers (Blackledge & Creese, 2017), which can provide insight into how emerging bilingual students could use gestures when learning science. To understand the function that gestures could play in science learning, it is important to recognize that scientists themselves rely on gesturing when sharing their ideas and engaging with colleagues (e.g., Ochs, Jacoby, & Gonzalez, 1994; Roth, 1996, 2001). Specifically, research suggests that scientists deploy deictic gestures when trying to orient each other to salient entities and/or crucial features of graphical representations of ideas (Roth, 2001). Moreover, scientists use iconic and/or metaphoric gestures when discussing abstract concepts that are difficult to convey through speech (Lemke, 1999). The way gestures feature into scientists’ exchanges highlight two considerations for science learning environments. Like scientists, students can rely on multiple dimensions of gesturing when communicating their observations and/or explanations about the natural world. And, since gestures are part of the semiotic repertoire students draw from, rather
than mere ornaments of speech, they should be considered as productive communicative resources for students to use when engaging in epistemic practices of science.

Particular to science learning environments, Roth (1996, 2001) has described how students use gestures for sharing their ideas. For example, when studying how middle school students made sense of simple machines, Roth (1996) observed that students used deictic gestures when describing how a pulley system could reduce the amount of force needed to move heavy objects, as they pointed to a diagram of the machine they were studying. Roth also observed that students used iconic gestures when representing the motion of an object due to the presence of a force. Similarly, when investigating how high schoolers used a visual display to understand accelerated motion, Roth (2001) observed that students performed multiple dimensions of gestures when describing how an object moved. Specifically, Roth observed how one student pointed to different parts of the screen (deictic gesture) when talking about the object and its path, and performed iconic gestures that resembled the object’s trajectory. These studies led Roth to conclude that gestures are central to communication and discussion of ideas about physical phenomena, rather than auxiliary and dispensable; the hand can represent imperceptible entities, while the hand’s motion can stand for the activity the entities are involved in.

*Translanguaging*, then, could be a powerful construct for understanding how emerging bilingual students draw from an expansive semiotic repertoire in the service of making sense of and co-constructing knowledge about the natural world. Relying on both linguistic (e.g., named languages) and non-linguistic (e.g., gestures) resources, emerging bilingual students could effectively communicate their ideas and explanations about the natural phenomena they are observing and investigating. And yet, we know little about what translanguaging looks like for emerging bilingual students in science learning environments; we know the most about their use
of linguistic resources when engaging in science-based literacy activities. This study contributes to the field’s understanding of the complexity of translanguaging in science learning environments, through addressing the following research questions:

1. What are the semiotic resources emerging bilingual students leverage when engaging translanguaging practices in the service of describing or explaining electrical phenomena?
2. What are some of the purposes did students’ translanguaging practices serve when collaboratively exploring electrical phenomena?
3. How did the instructor make this science learning environment a translanguaging space in which students could use their full semiotic repertoires, or not?

METHODOLOGY

Context and Participants

This study took place in partnership with a local library system, working with elementary-aged emerging bilingual learners (predominantly from grades 3-5). Library administrators were excited and supportive of creating an out-of-school time science-based program for their younger patrons, especially one that would run for a sustained period of time and would serve bilingual children in the community. The program was offered three times throughout 2016 (Spring, Summer, Fall), at different library branches that serve predominantly immigrant families. For the purpose of this study, I will focus on the implementation at only one of the library branches: Dexter. This library branch serves a neighborhood of predominantly African-American and immigrant families from Latin America (e.g., Mexico), Sub-Saharan Africa (e.g., Ethiopia), and East Asia (e.g., Burma). During the summer 2016 iteration, the program recruited ten (10) learners, spanning grades 1<sup>st</sup> through 5<sup>th</sup>; attendance varied throughout the program and not all children were present at every session. All participating students were emerging bilingual and represented a wide range of home languages, including Spanish, Arabic, and Somali.
Only four (4) of the students consented to participate in the research, and were present during the sessions I analyzed. These students were (pseudonyms): Yesenia, a Latina 4th grader, and her brother Elio who was in 2nd-grade, both of whom spoke Spanish and English; and Toben, a 4th-grade Nigerian-Japanese student, and his sister Grace, who also was in 2nd grade, both of whom spoke English and some Japanese. I was the program’s instructor, and my semiotic repertoire includes resources from Spanish and English. For most of the program, Yesenia and Elio worked together on their experiments and explanations, and Toben and Grace worked together, as well. Eventually students would tire of working with their siblings, and requested pairing off with another student, or do the investigations individually. I was committed to making the program a translanguaging space and regularly encouraged students to use linguistic resources from their full repertoires, especially those associated with their home languages when working with their sibling. Implicitly and expectedly, English became the program’s *lingua franca*.

**Data Collection**

For this study, I collected data from two main streams: video and audio recordings of classroom interactions, and student-produced artifacts. I prioritized video data because it could yield the most information on students’ translanguaging practices when investigating and discussing the electrical phenomena they observed. The video data was collected using two video cameras and their positioning depended on the type of activity students engaged in. During the beginning of each session, when there was a brief whole-group conversation about the session’s investigation, the camera remained stationary on a tripod and pointed towards the whole group (non-consenting students were excluded). This positioning of the camera was intended to capture students’ ideas and gesturing when interacting with other students. When students investigated different electrical phenomena in small groups, a camera was pointed towards each group’s work area. Cameras remained stationary on a tripod and pointed towards the center of the area where
the groups of students were working. This angle was best for capturing students’ translanguaging practices when investigating electrical phenomena. Finally, during whole-group discussions at the end of each activity, students sat around the work table with the investigation materials within reach and other inscriptions they produced. The camera was positioned facing the students in order to capture their ideas. I panned and zoomed as needed, in order to capture how students used their representations to support the sharing of their reasoning.

In addition to video and audio recordings of the activities, I collected still images of the work students produced while engaging in the investigations, like written text on white boards, drawings, and even the experimental setups they designed for collecting data to address the sessions’ driving questions. These student-produced artifacts helped me explore students’ translanguaging practices across modalities (e.g., written, spoken) for sharing their reasoning.

Data Analysis

My approach to analyzing the collected data was qualitative in nature (M. Miles et al., 2013). The first step in the retrospective analysis was to condense the data by creating content logs that summarized the video and audio recordings by dividing these data into 5-minute segments. Each entry described students’ participation and communication in the investigation, focusing on how students engaged in translanguaging practices. The second step in the analysis was to identify the moments in which students were using their full semiotic repertoire, or aspects of it. The unit of analysis was the exchange, defined as an interaction between two or more speakers (i.e., students, instructor) through using the full, or aspects of, their semiotic repertoires (Stevenson, 2013, 2015). An exchange could range from a one-sentence utterance to a multiple-turn interaction, and was bound by a change in activity or topic of discussion. To understand how students used linguistic resources when translanguaging, I identified moments in which students transitioned between named languages during an exchange (e.g., English to Spanish), either in
spoken or written form. I made this analytical choice based on the assumption that the use of two named languages in close temporal proximity indexed students drawing on various linguistic resources from their full repertoires. As I will discuss below, this analytical decision was not without consequences, mainly embodying a monoglossic view of bilingualism in the analysis. After identifying these exchanges, I quantified how many transitions occurred during each 5-minute segment of video. The results from the coding allowed me to create a map of when students externally engaged in translanguaging during each session, and the whole program. This information helped me understand whether translanguaging through linguistic resources was ubiquitous, and the conditions that might have supported it.

Additionally, I focused my analysis on moments when students were translanguaging through using gestures, which I operationalized as: any body movement, specifically involving the hands and/or arms, which serves to describe an observation or present an explanation. I identified exchanges in which used gestures when communicating their observations and/or reasoning, used three dimensions of gesturing (D. McNeill, 1992, 2005) as deductive codes for characterizing how students used gestures when communicating their observations and ideas about electrical phenomena (see Table 4.1); beats were excluded because they are exclusively used for structuring and/or emphasizing talk, rather than communicating propositional nor topical content. After identifying these exchanges, I quantified how many of each type of gesture occurred during each 5-minute segment of video. Using the results from the coding, I created a graphical representation of when students used gestures when sharing their observations and reasoning, which helped me understand how ubiquitous gesturing was throughout the program.

Table 4.1: Dimensions of gestures as deductive codes for identifying and describing students’ gesturing.

<table>
<thead>
<tr>
<th>Dimension of Gesture</th>
<th>Sample of Coded Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deictic</td>
<td>“The energy comes through the wires ((touches one of the connected wires)) and then you put on the metal things and it would go right here ((touches where the wire is clamped to the lead of the lamp holder)).”</td>
</tr>
</tbody>
</table>
Iconic

“If it’s fatter ((moves thumb and index fingers apart from each other)), more electricity can flow faster.”

Metaphoric

“And the energy from the battery causes the whole thing to run ((moves hand in a circle above the complete circuit)) perfectly.”

The final stage in the analysis was to code the translanguage exchanges, specifically those where students leveraged linguistic resources, according to the goals they oriented towards. I chose to only analyze exchanges where students transitioned between named languages because I wanted to understand possible conditions imposed on students’ full semiotic repertoire, particularly by (inadvertently) associating some linguistic resources with specific collaborative goals. For example, it would be important to understand if students used linguistic resources associated with Spanish for both organizing the social world and making sense of the natural one. This analytical choice does not assume that students’ translanguage through leveraging non-linguistic resources (e.g., gestures) would not serve different collaborative purposes. I build on the shared epistemic goals framework (Damşa, Kirschner, Andriessen, Erkens, & Sins, 2010) to distinguish between translanguage practices that served different functions within students’ participation and collaboration. Based on Damşa et al.’s work, for this study I define epistemic goals as activity goals aimed at creating and evaluating science knowledge, while regulative goals are activity goals with the purpose to manage the collaboration itself. I used epistemic and regulative as deductive codes for classifying the exchanges based on their function in the collaborative work; I also developed inductive sub-codes to categorize how students regulated their work, as well as presented and evaluated ideas about the circuits (see Table 4.2). This coding allowed me to identify and distinguish between the functions translanguage practices served within the context of collaborative work, especially when it was student-initiated. Quantifying the exchanges that fell under each category served to paint a picture of how students used linguistic resources and gesturing for regulative and/or epistemic purposes.
Table 4.2: Codes for distinguishing the collaborative goals achieved by students’ translanguaging.

<table>
<thead>
<tr>
<th>Primary Code</th>
<th>Definition</th>
<th>Sub-codes</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulative</td>
<td>Organizing the surrounding social world</td>
<td>Behavior</td>
<td>Directives for managing behavior</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Division of Labor</td>
<td>Deciding who does what type of work when collaborating</td>
</tr>
<tr>
<td>Epistemic</td>
<td>Co-constructing knowledge about the natural world</td>
<td>Presenting</td>
<td>Students share their ideas and reasoning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evaluating</td>
<td>Students evaluate other students’ ideas</td>
</tr>
</tbody>
</table>

FINDINGS AND ANALYSIS

Throughout the program, students engaged in different kinds of translanguaging practices during exchanges with each other and the instructor. Some of these were spontaneously initiated by students and others were in response to the instructor’s own translanguaging moves. Here, I present findings from the analysis on the semiotic resources students leveraged when translanguaging while sharing their thinking about electrical phenomena. Additionally, I analyze the exchanges when students spontaneously engaged in translanguaging through linguistic resources, attending to how students’ translanguaging served different purposes in the collaborative work. Finally, I present the analysis of the instructor’s pedagogical moves that seemed to support students to engage in translanguaging practices, focusing on one session.

Students engaging in translanguaging practices: leveraging multiple linguistic resources

Throughout the program, there were multiple instances when students engaged in translanguaging through leveraging multiple semiotic resources. However, Yesenia and Elio were the only two students who used linguistic resources associated with named languages; Toben and Grace engaged in translanguaging only through gestures, a portion of their full semiotic repertoires (see Table 4.3).

Table 4.3: Comparing number of exchanges in which students engaged in translanguaging practices through linguistic resources.

<table>
<thead>
<tr>
<th>Student</th>
<th>Number of exchanges with transitions between languages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toben</td>
<td>0</td>
</tr>
<tr>
<td>Grace</td>
<td>0</td>
</tr>
<tr>
<td>Elio</td>
<td>15</td>
</tr>
<tr>
<td>Yesenia</td>
<td>19</td>
</tr>
</tbody>
</table>
Yesenia and Elio used linguistic resources from their semiotic repertoire on multiple occasions throughout the program (see Figure 4.1). Specifically, Yesenia and Elio used linguistic resources from English and Spanish when participating in the sessions’ activities, as they collaborated with each other or engaged with the instructor. The sustained presence of translanguaging practices throughout the program indicates that Yesenia and Elio had opportunities to draw from multiple linguistic resources as they explored and made sense of electrical phenomena, suggesting the learning environment became a translanguaging space for them. As I will discuss below, the learning environment may not have created favorable conditions to support Toben and Grace’s translanguaging through multiple linguistic resources.

![Yesenia and Elio Transition Between English and Spanish](image)

Figure 4.1: Times that Yesenia and Elio transitioned between English and Spanish, indexing translanguaging through linguistic resources. *Session 4 was the first session Yesenia and Elio joined; they transnguaged 5 times when telling the instructor about a wire loop puzzle (simple circuit) played with, before Toben and Grace arrived.

I present below two examples to describe Yesenia and Elio’s translanguaging practices: one that shows how they used both speech and text for translanguaging when working together, and another one that shows an interaction between Yesenia and the instructor. Session 4 was Yesenia and Elio’s first session in the program, and the instructor decided to review some of the discussions about electrical circuits that Toben and Grace had already had. After students had connected a circuit using wires, batteries, and lamps, the instructor asked them to come up with an explanation for how they thought the electricity traveled through the circuit; the instructor
provided students with white boards and markers, and asked them to write and/or draw their ideas. The white boards were introduced as a medium for students to collect and present their thinking through writing and/or drawings; students were not obligated to use the white boards, but where encouraged to do so when sharing with others. The following excerpt\(^8\) depicts how Yesenia and Elio engaged in translanguaging when constructing their ideas about electric flow:

Excerpt 1: Elio and Yesenia think about what the battery does in the circuit (Session 4)

<table>
<thead>
<tr>
<th>Lines</th>
<th>Speaker</th>
<th>Utterance (translation in English)</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yesenia</td>
<td>Se está prendiendo porque… (it is turning on because…)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Elio</td>
<td>La batería está haciendo energía para que prenda (the battery is making energy for it to turn on)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Yesenia</td>
<td>Writes on whiteboard: The battery</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Elio</td>
<td>Generates. Ponle generates (add generates)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Yesenia</td>
<td>Eso es una palabra… (that is a word that…)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Yesenia</td>
<td>Writes on whiteboard: generates energy but without</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Elio</td>
<td>Generate es con silent E (Generates has a silent e)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Yesenia</td>
<td>“The battery generates energy but without”</td>
<td>Reading the white board</td>
</tr>
<tr>
<td>9</td>
<td>Elio</td>
<td>¿But without qué? (But without what?)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Yesenia</td>
<td>Writes on whiteboard: the battery the bulb won’t light up</td>
<td></td>
</tr>
</tbody>
</table>

In this interaction, Yesenia and Elio discussed the electric flow through the circuit, in particular the role the battery played, as they drew on multiple linguistic resources. Managing speaking Spanish and writing in English indexes how Yesenia and Elio engaged in translanguaging practices through leveraging multiple linguistic resources. First, Elio suggested in Spanish that the battery generated the energy\(^9\) that would run through the circuit and eventually turn on the lamp (Excerpt 1, line 2); Yesenia listened to this idea and began writing it on the white board in English (Excerpt 1, line 3). As she kept working on the board, Elio attended to the content and grammar of what Yesenia was writing, suggesting a word in English.

---

\(^8\) Transcription conventions: - self interruption; … pause; (   ) translations; [] deictic terms ; ((   )) gestures; other punctuation added for increasing readability.

\(^9\) While it is sensible to assume that students meant “electricity” when saying “energy,” I will use the energy throughout this article to avoid erroneous assumptions about what students meant and honor their linguistic choice.
he deemed appropriate, “Ponle generates” (Excerpt 1, line 4), and then checking whether it was spelled correctly, “Generates es con slient E” (Excerpt 1, line 7). These contributions exemplify how Elio drew on linguistic resources associated with Spanish and English and exercised metalinguistic awareness to make sure his sister’s writing was consistent with what he was saying. Without previously discussing it with Elio, Yesenia included a caveat as she continued to write their explanation of electric flow, “generates energy but without…” (Excerpt 1, line 6), prompting Elio to engage with her reasoning and determine what she was thinking about, “But without qué?” (Excerpt 1, line 9). Again, Elio drew on multiple linguistic resources when reading Yesenia’s writing in English, recognizing that there was something missing from the text, and asked a follow-up question using resources associated with English and Spanish. Once Yesenia was done writing, the text read, “the battery generates energy but without the battery the bulb won’t light up,” (Excerpt 1, line 10), suggesting that Yesenia agreed with Elio’s idea about the indispensability of the battery for the functioning of the circuit.

Through spoken and written forms, Yesenia and Elio engaged in translanguaging practices, fluidly drawing from multiple linguistic resources, when problematizing the battery’s role in the flow of electricity. Moreover, Yesenia and Elio seemed aware of which linguistic resources to draw on depending on which activity they engaged in. When working together, they leveraged linguistic resources associated with both English and Spanish, as they discussed how the electricity flowed through the circuit. When writing and drawing their ideas for sharing them with Toben and Grace, though, Yesenia and Elio only used English, perhaps acknowledging that these were where the only linguistic resources they shared with their peers. In effect, Yesenia and Elio deployed linguistic resources to accommodate their audience and facilitate communication, in accordance to what other research has reported (Martínez, 2010; Stevenson, 2013, 2015).
Yesenia and Elio also engaged in translanguaging practices through leveraging multiple linguistic resources when sharing their ideas about electrical circuits. The example I present below comes from the last session of the program (Session 8), when students used gel pens that contained conductive ink (Russo et al., 2011) to draw circuits that worked just the same as wired circuits (for the full study design see: Suárez, dissertation chapter). Specifically, students were investigating how the thickness of line of conductive ink regulated how much energy flowed through the circuit. Yesenia drew a few circuits with different thicknesses and compared how the lamp’s brightness changed as a function of the lines’ thickness, observing that the lamp shone dimmer when connected to the thinner circuit than when connected to the thicker circuit. The instructor noticed the marked differences in brightness, and the following exchange ensued:

Excerpt 2: Yesenia explains how a line’s thickness regulates electric flow through the circuit (Session 8)

<table>
<thead>
<tr>
<th>Lines</th>
<th>Speaker</th>
<th>Utterance (translation in English)</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Instructor</td>
<td>¿Qué estás pensando? (Let’s see, Yesenia. Show me. What are you thinking?)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Yesenia</td>
<td>La energía puede ir más rápido en este lado (The energy can go faster on [thick conductor])</td>
<td>Points to thick conductor</td>
</tr>
<tr>
<td>3</td>
<td>Yesenia</td>
<td>que en este lado… (than on this side [thin conductor])</td>
<td>Points to thin conductor</td>
</tr>
<tr>
<td>4</td>
<td>Yesenia</td>
<td>porque está muy chiquito y hay menos espacio para que la electricidad vaya, y aquí hay más espacio (because it [thin conductor] is very small and there is less space for the electricity to go, and here [thick conductor] there is more space.)</td>
<td>Points to thick conductor</td>
</tr>
<tr>
<td>5</td>
<td>Yesenia</td>
<td>Entonces está más fácil que vaya acá (So, it is easier for it to go here [thick conductor].)</td>
<td>Points to thick conductor</td>
</tr>
<tr>
<td>6</td>
<td>Yesenia</td>
<td>pero a veces se atora aquí (but sometimes it gets stuck here [thin conductor])</td>
<td>Points to thin conductor</td>
</tr>
<tr>
<td>7</td>
<td>Yesenia</td>
<td>y no puede volver a la batería. (and it can’t go back to the battery)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Instructor</td>
<td>O sea, puede pasar por uno (So, it can through one)</td>
<td>Points to thick conductor</td>
</tr>
<tr>
<td>9</td>
<td>Instructor</td>
<td>but it can’t go through the other one, kind of a thing.</td>
<td>Points to thin conductor</td>
</tr>
<tr>
<td>10</td>
<td>Instructor</td>
<td>How come – what do you think was happening when you had these two big ones?</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Yesenia</td>
<td>It would be easier and it [electricity] could go faster.</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Instructor</td>
<td>It could go faster both ways? And what about this one, this thin one?</td>
<td></td>
</tr>
</tbody>
</table>
The instructor began by asking Yesenia to explain her observations, in Spanish, “¿Qué estás pensando?” (Excerpt 2, line 1). Yesenia continued in Spanish and proceeded to present her reasoning about how the lines’ thickness affected how much electricity was flowing through, stating that thinner lines would make it harder for electricity to move through because it could get stuck and, thus, interrupt the electric flow; whereas, thicker lines provided the electricity with plenty of space to move through, without losing speed (Excerpt 2, lines 2-7). Yesenia constructed a rich explanation that included a sequencing of events and described in detail how the lines’ thickness determined how much space was available for the electricity to move through the circuit at different speeds, and whether it would get stuck along the way. In essence, Yesenia presented a mechanistic account (MacHamer et al., 2000) of how the conditions of the system (i.e., lines’ thickness) determined the activities (i.e., flow) the main entity (i.e., electricity) engaged in and gave rise to the phenomena she was observing (i.e., differences in the lamp’s brightness). Yesenia’s account was richer and more complete than a causal explanation (Russ et al., 2008), such as “thin lines make the lamp dimmer”, given that she identified salient processes and their sequencing in order to explain what she observed.

The instructor proceeded to summarize and clarify Yesenia’s reasoning, which he did while drawing from linguistic resources associated with Spanish and English, respectively: the electricity could move through the thick line (Excerpt 2, line 8), but not the thin one (Excerpt 2, line 9). As the instructor spoke, he transitioned Spanish into using linguistic resources associated with English. Perhaps in an effort to accommodate the instructor’s speech (Stevenson, 2013, 2015), Yesenia also transitioned to using linguistic resources associated with English and repeated her explanation. Specifically, Yesenia repeated once again that the thicker line would
make it easier for the electricity to flow through, allowing it to move faster through the circuit (Excerpt 2, line 11); the thinner lines would make it harder and, therefore, it would take longer for the electricity to move through (Excerpt 2, line 13). This portion of the exchange between Yesenia and the instructor stands out for a few reasons. First, Yesenia’s explanation using linguistic resources associated with English was similar and as rich as the explanation she presented when using linguistic resources associated with Spanish. The consistency of Yesenia’s explanation across named languages suggests that she was skilled at drawing from her full semiotic repertoire when constructing this explanation. Perhaps, her choice of Spanish or English was associated with what she might have interpreted as the instructor’s expectations for which linguistic resources to use. I elaborate further on this issue in an upcoming subsection. Secondly, Yesenia’s translanguaging throughout this excerpt shows the importance of considering how speakers draw from a broader semiotic repertoire when communicating, which includes both linguistic and non-linguistic semiotic resources. Specifically, Yesenia used a combination of speech and gesturing, particularly pointing to the different lines, when sharing her reasoning about how the lines’ thickness made a difference. In this case, Yesenia’s pointing served to disambiguate her speech (Roth, 1996, 2001), highlighting for the instructor exactly which line she was referring to when sharing her reasoning.

**Students engaging in translanguaging practices: leveraging gestures**

In addition to drawing from linguistic resources associated with different named languages, students also resorted to gesturing when describing their observations and presenting their reasoning about electrical phenomena. Based on the initial coding of exchanges between students, and between students and the instructor, it became clear that gesturing was ubiquitous throughout the program (see Figure 4.2). The sustained presence of multiple dimensions of gesturing throughout the program suggests that the learning environment acted as a
translanguaging space, one in which all students could leverage their semiotic repertoire when sharing their thinking about the electrical phenomena they observed. Figure 4.2 shows that students did not use all dimensions of gesturing in each session; perhaps the nature of the activities students engaged in during each session promoted differential uses of gestures.

As I described before, the exchange between Yesenia and the instructor (Excerpt 2) provided initial insight into how students used gestures when translanguaging to present their ideas. To further understand how students used different dimensions of gesturing throughout the program, I analyze three examples of students’ gesturing when sharing their ideas about electric flow.

The first example focuses on how Grace leveraged multiple semiotic resources when sharing her account for how electricity flowed through a circuit. This episode happened during Session 3, when Toben and Grace constructed a model for electric flow. The instructor asked Grace how she thought the electricity flowed through the circuit, prompting the following contribution:
Excerpt 3: Grace describes how she thinks electricity flows through a circuit. (Session 3)  
(Yellow arrows represent motion and its direction; Red arrows represent hands are stationary)

<table>
<thead>
<tr>
<th>Line</th>
<th>Time</th>
<th>Utterances ((gestures))</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>00:24:15</td>
<td>Grace: If you connect them right here ((touches each side of the battery))</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>2</td>
<td>00:24:17</td>
<td>Grace: it [electricity] bounces off here and it [electricity] goes ((tracing wires with fingers))</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grace's mutters something inaudible</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>00:24:30</td>
<td>Grace: It [electricity] goes all the way ((tracing wires with fingers))</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>4</td>
<td>00:24:32</td>
<td>Grace: over here ((touches lamp))</td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>5</td>
<td>00:24:37</td>
<td>Grace: and then they’re the same ((connects wire to lamp and lights it up))</td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>6</td>
<td>00:24:39</td>
<td>Instructor: And then they meet there [the battery]?</td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>7</td>
<td>00:24:40</td>
<td>Grace: Yes!</td>
<td><img src="image7.png" alt="Image" /></td>
</tr>
<tr>
<td>8</td>
<td>00:24:41</td>
<td>Instructor: So, you’re saying it’s coming out from here [black wire] and here [red wire] at the same time, and then they travel, and then they meet at the light bulb.</td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>9</td>
<td>00:24:46</td>
<td>Grace: Yeah.</td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>10</td>
<td>00:24:47</td>
<td>Instructor: Do you agree with that, Toben? Do you think it’s going through both wires at the same time, or do you think it goes a different way?</td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
<tr>
<td>11</td>
<td>00:24:55</td>
<td>Toben: This one [red wire] goes first</td>
<td><img src="image11.png" alt="Image" /></td>
</tr>
<tr>
<td>Time</td>
<td>Description</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>00:24:57</td>
<td>Toben: And this one [black wire] goes second</td>
<td></td>
<td></td>
</tr>
<tr>
<td>00:25:03</td>
<td>Toben: Coz if they go both, it might not make it um - make the light bulb not turn on and it might get messed up.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>00:25:16</td>
<td>Grace: I think so because ((points to lamp))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>00:25:17</td>
<td>Grace: it keeps on going ((traces wires with fingers, towards the battery))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>00:25:18</td>
<td>Grace: like that ((points to the battery))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>00:25:20</td>
<td>Grace: ((traces wires with fingers))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>00:25:20</td>
<td>Grace: and it meets here ((points to the lamp))</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The process Grace described first required that the wires were connected to the battery, which she alluded to by touching each side of the battery (deictic gesture) as she spoke (Excerpt 3, line 1). Once the wires were connected, Grace traced each wire with a finger, moving her hands away from the battery and towards the lamp (Excerpt 3, lines 2-3); through these metaphoric gestures, Grace illustrated the invisible and abstract concept of electric flow, specifically how each wire carried electricity independently at the same time. Her next statement was that the two streams of electricity met at the lamp, which she said as she touched the lamp.
(deictic gesture), connected the wires and lighting it up (Excerpt 3, lines 4-5). Grace described how she thought the electricity moved from the battery to the lamp, by gesturing while speaking.

When the instructor asked Toben what he thought of Grace’s claim (Excerpt 3, line 10), he claimed that each wire would carry electricity at different times: he said electricity moved through the red wire first, as he traced it with his finger (Excerpt 3, line 11), and then traveling through the black wire, as he traced his finger over it (Excerpt 3, line 12). Through these two metaphorical gestures, Toben illustrated how he thought electricity flowed from the battery, through each wire at different times, and towards the light bulb. Toben further added that if electricity were to travel simultaneously through each wire, as Grace’s model suggested, the circuit would get “mess ed up” (Excerpt 3, line 13) In response, Grace pointed to the lamp (deictic gesture), signaling the point of departure in this recursive process (Excerpt 3, line 14). From the lamp, Grace traced each wire with her finger, moving her hands away from the lamp and towards the battery (metaphorical gesture), until she reached and pointed to the battery (deictic gesture) (Excerpt 3, lines 15-16). Through these hand motions, Grace represented again how the electricity moved simultaneously through each wire and returned to the battery. Finally, starting from the battery, Grace traced each wire with her hands once more (Excerpt 3, line 17), ending at the lamp, which Grace pointed to (deictic gesture) when stating that the electricity from each wire met there (Excerpt 3, line 18). Grace addressed Toben’s concern about the electricity from each wire reaching the lamp simultaneously. To further bolster he claim, Grace added, “If it went one at the time it would go like this [red wire] it would turn on, and then the other one [black wire] and it would turn on. That’s why I think it goes at the same time” (Session 3).

In effect, Grace described a detailed mechanistic account (Russ et al., 2008) that resembled the “Clashing Currents” model of electricity moving through a circuit (R. Osborne, 1983;
Peppler & Glosson, 2013). By marshalling speech and gestures, Grace highlighted the salient entities (e.g., electricity, wires), described the sequencing of events of how the lamp turned on, and illustrated the abstract concept of electric flow. To illustrate the function of her gestures, let us isolate Grace’s speech from the gestures she enacted while speaking (see Table 4.4).

Table 4.4: Comparing the meaning that can be derives from Grace’s statements without and with gestures

<table>
<thead>
<tr>
<th>Lines</th>
<th>Grace’s Speech</th>
<th>Inferred Model: Speech + Gesturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Grace: If you connect them</td>
<td>Wires need to be connected at each side of the battery.</td>
</tr>
<tr>
<td>2-4</td>
<td>Grace: it [electricity] bounces off here and it [electricity] goes … it [electricity] goes all the way … over here.</td>
<td>Electricity flows from the battery to the lamp through each wire separately.</td>
</tr>
<tr>
<td>5</td>
<td>Grace: and then they’re the same</td>
<td>Each wire carries the same amount of electricity.</td>
</tr>
<tr>
<td>14-18</td>
<td>Grace: I think so because … it keeps on going … like that … and it meets here.</td>
<td>Electricity recursively moves from the battery to the lamp, through the wires, and back.</td>
</tr>
</tbody>
</table>

It is difficult to do a one-to-one correspondence between Grace’s statements and her model of electric flow without having access to her gestures, and observe how she is moving her hands while talking in relation to the tangible tools in front of her. Taking the last five utterances as an example (Excerpt 3, lines 14-18), Grace refers to the electricity “going on … like that,” but without access to her gesturing we cannot know what exactly “like that” means. Similarly, Grace states “it meets here,” which is difficult to understand through her speech alone because the deictic term “here” is imprecise and can only be disambiguated through pointing. This suggests that leveraging multiple resources from a larger semiotic repertoire supported Grace sharing her thinking about how electricity flowed through the circuit she was exploring. Moreover, the tangible circuit on the table seemed to support her translanguaging, serving as a reference point for Grace and Toben’s gesturing, allowing their audience to disambiguate what their deictic and metaphoric gestures meant (Roth, 2001).

Yesenia also performed a series of gestures similar to Grace’s, when illustrating how electricity flowed through each of two parallel circuits that Graced had connected, each with a
lamp of different wattage. Toben asked why the one lamp shone brighter than the other, and Yesenia offered the following explanation:

**Excerpt 4: Yesenia narrates how electricity moves through a wired circuit (Session 4)**

09:08 Yesenia So, this one ((touches bright lamp)) creates more energy…
09:12 Yesenia than this one ((touches dim lamp)) because…
09:15 Yesenia Um, they…
09:20 Yesenia They go the same.
09:25 Yesenia This one goes through here ((touches clamps and traces yellow wire)) (Figure 4.3, panel 1-3)
09:27 Yesenia And this one goes through here ((touches clamps and traces black wire)) (Figure 4.3, panel 4-6)
09:31 Yesenia So, there’s more current here ((touches bright lamp)) than here ((touches dim lamp))

![Figure 4.3](image.png)

Figure 4.3: Yesenia traces the different wires as she describes how electricity moves through each circuit. (Yellow arrows represent circular motion and its direction; Red arrows represent hand is stationary).

Yesenia engaged in translanguaging practices that included linguistic resources and gestures to illustrate how she thought “the energy” flowed through the wires connected to the brighter lamp. She began by touching where the yellow wire was connected to the battery (deictic gesture), and then traced the wire (metaphoric gesture) all the way to where it was connected to the lamp holder (Figure 4.3, panels 1-3). Yesenia switched from the yellow clamp to touching the black one (deictic gestures), and traced the black wire (metaphoric gesture) all the way back to where it was connected to the battery (Figure 4.3, panels, 4-6). By moving her hand along the yellow and black wires, Yesenia illustrated how she thought energy moved through that circuit.
Yesenia also depicted how she thought electricity flowed through an imaginary circuit by enacting metaphoric gestures. After seeing the lamp turn on immediately after completing the circuit, Yesenia offered the following explanation:

Excerpt 5: Yesenia describes how electricity flows through an abstract circuit (Session 4)

01:18 Yesenia Energy is ru – (Figure 4.4, panels 1-3)
01:19 Yesenia It always runs very quickly. (Figure 4.4, panels 4-6)
01:22 Yesenia And so… (Figure 4.4, panel 7)
01:25 Yesenia it makes the light bulb… (Figure 4.4, panels 8-9)
01:28 Yesenia light up because it’s going so quickly you can see it…

Figure 4.4: Yesenia moves her right hand in a circle as she talks about why the lamp turns on. (Yellow curved arrows represent circular motion and its direction; Red arrows represent hand is stationary).

Yesenia’s explanation began with a reminder that electricity runs through the circuit, which she expressed through a combination of speech and gestures that illustrated how energy moved in a circle (Figure 4.4, panels 1-3). This first statement shows how integral gestures are to Yesenia’s communication, specifically by how she could substitute speech for gestures when communicating that energy flowed in circles. Yesenia then added that energy runs fast, as she quickly moved her right hand in a circular motion, completing three circles in a handful of seconds (Figure 4.4, panels 4-6). Yesenia conveyed two messages about the energy through these gestures: she illustrated that energy traveled in a circular path through an imaginary circuit (one
she did not reference in her speech), and that the energy traveled through it very quickly. She performed similar gestures a few seconds later, when claiming that the fast-moving energy would make the lamp light up (Figure 4.4, panels 8-9). She moved her hand again in a circle to represent the energy that flowed through the circuit, even if she did not explicitly mention the energy’s path (implicit in the gestures’ directionality). Yesenia’s contribution is characterized by her use of multiple communicative resources (i.e., speech and gestures), all of which comprised her larger semiotic repertoire. This suggests that the learning environment was a translanguaging space, in which the students could freely express multiple ideas about how electric flow.

Translanguaging through linguistic resources served different collaborative purposes

So far, I have focused my analysis on exchanges where students engaged in translanguaging practices when sharing their ideas about electrical phenomena (i.e., epistemic purposes), leveraging both linguistic and non-linguistic resources. However, not all of the exchanges characterized by translanguaging served epistemic goals, given that students also engaged in translanguaging when organizing social aspects of their collaboration. As stated above, I chose to analyze the exchanges where students engaged in translanguaging practices through leveraging multiple linguistic resources, particularly those when students spontaneously transitioned between named languages. The purpose was to identify whether there were implicit conditions that dictated when and how students drew from their semiotic repertoire. I coded these exchanges according to whether students’ translanguaging served specific collaborative purposes (see Table 4.2): managing behavior (regulative), dividing labor (regulative), sharing an idea (epistemic), and/or evaluating an idea (epistemic). This analysis focuses only on Yesenia and Elio, given that they were the only students who translanguaged using linguistic resources associated with more than one named language.
As Table 4.5 shows, over 60% of the exchanges where Yesenia and Elio spontaneously transitioned between English and Spanish to address each other served regulative goals (e.g., managing behavior, dividing the labor), rather than epistemic goals for co-constructing knowledge.

Table 4.5: Number of exchanges, per session, where Yesenia and Elio spontaneously transitioned between English and Spanish to address each other, classified according to the goals their translanguaging served. These data include counts for the first-level codes (regulative and epistemic), as well as counts for their respective sub-codes (managing behavior, division of labor, sharing ideas); there were no exchanges where students evaluated each other’s ideas through as they transitioned between English and Spanish.

<table>
<thead>
<tr>
<th></th>
<th>Translanguaging Exchanges: Regulative</th>
<th>Translanguaging Exchanges: Epistemic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yesenia</td>
<td>Elio</td>
</tr>
<tr>
<td></td>
<td>Behavior</td>
<td>Labor</td>
</tr>
<tr>
<td>Session 4</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Session 5</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Session 6</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Session 7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Session 8</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4</strong></td>
<td><strong>2</strong></td>
</tr>
</tbody>
</table>

When regulating each other’s behavior, Yesenia would normally issue one-turn behavior instructions for her brother Elio, such as, “Elio, ve y siéntate allá (Elio, go sit over there)” (Session 5); they would return to using English after Elio had obeyed the command. Yesenia and Elio also used Spanish to manage their collaboration, particularly when dividing the labor each of them would perform. For example, when they were writing and drawing on the white board their explanation for the battery’s function in the circuit (see Excerpt 1), Yesenia asked Elio: “dibuja los cables usando el marcador azul (draw the wires using the blue marker)” (Session 4). The observation that Yesenia and Elio spontaneously transitioned between English and Spanish to achieve regulative goals more often than epistemic ones suggests that they used specific portions of their linguistic repertoires for different purposes. Specifically, the difference in the functional goals of each system suggests that these students thought of Spanish as reserved for regulative goals, while English served epistemic goals. And while regulative actions are
important for creating the infrastructure for epistemic work, it is telling that students spontaneously used Spanish predominantly for organizing the social world. These data also suggest that Yesenia and Elio exercised metalinguistic awareness, choosing the linguistic resources they thought appropriate to fit specific contextual features.

Instructor moves that supported students to engage in translanguaging

While the learning environment served as a translanguaging space, where students could leverage linguistic and non-linguistic resources from their semiotic repertoires, the analysis thus far shows that these opportunities were not available to all students, during all sessions. Therefore, it is important to understand how the instructor’s pedagogical moves supported students’ translanguaging. Mapping the occurrence of students’ translanguaging throughout the program reveals the differential opportunities for students to use various aspects of their semiotic repertoires for sense-making. Focusing on students’ gesturing, all students were able to deploy these non-linguistic resources when sharing their ideas with others (Figure 4.2). On the other hand, Table 4.3 and Figure 4.6 reveal that not all students had opportunities for translanguaging through using multiple linguistic resources, in particular those associated with various named languages. In particular, Session 7 had the lowest number of translanguaging exchanges using linguistic resources (i.e., transitions between named languages) of the program (n = 2). While each session was different, what stands out the most about this session is that all four students were present at the same time: Yesenia and Elio, who shared resources associated with English and Spanish with the instructor; and Toben and Grace, who only shared resources associated with English with all participants. To better understand translanguaging in a variety of contexts, I differentiated between sessions with all students in attendance, and sessions where only Yesenia and Elio were present. The results are illustrated in the two figures below (Figures 4.5 and 4.6).
Figure 4.5: Number of exchanges with English-Spanish transitions in sessions where all four students were present. *Segments 1 and 2 from Session 4 occurred with just Yesenia and Elio in the room, before Toben and Grace arrived.

Figure 4.5: Number of exchanges with English-Spanish transitions in sessions where only Yesenia and Elio were present. *Segments 1–6 from Session 5 included a monolingual English-speaking student who left the program midway through segment 6, leaving Yesenia and Elio as the only students in the room.

Figure 4.5 shows that during the Sessions 4 and 7, when all four students were present, there were eleven exchanges when Yesenia and Elio transitioned between English and Spanish across the two sessions. However, as shown in Figure 4.6, during Sessions 5, 6, and 8, when Yesenia and Elio were the only students in attendance, the number of exchanges with transitions between Spanish and English increased to 23 across the three sessions. In other words, when all participants shared similar linguistic resources (e.g., Sessions 5, 6, and 8), the number of exchanges with English-Spanish transitions doubled, compared to the sessions when not all
linguistic resources were shared among the participants (e.g., Session 4 and 7). The increase in the number of exchanges that included transitions between named languages suggests that the availability of opportunities for translanguaging through leveraging linguistic resources associated with named languages depended on who was present. This increase could be partly due to the phenomenon discussed above, in which Yesenia and Elio leveraged linguistic resources associated with Spanish and English when working together (e.g., Figure 4.5, Session 4: segment 4), while being aware that they needed to share their thinking with Toben and Grace in English. At the same time, evidence suggests the instructor’s pedagogical moves had an effect.

To better understand how different contextual factors supported translanguaging, I analyzed the moments when students and the instructor leveraged different linguistic resources during the last session of the program (Session 8), which had the most exchanges with transitions between English and Spanish (n = 10). As mentioned before, during this session Yesenia and Elio were investigating how the width of the conductive lines’ thickness regulated how much electricity flowed through the circuit. The resulting timeline is shown in Figure 4.7, which reveals features about how the students and the instructor used linguistic resources. First, the graphical timeline shows the fluidity with which all participants used Spanish and English, leveraging linguistic resources associated with both named languages multiple times throughout the session. Excerpt 2 (analyzed above) illustrates what this type of translanguaging looked like in practice: Yesenia and the instructor leveraged both linguistic and non-linguistic resources when discussing how thinner conductive lines decreased the electric flow through the circuit (Figure 4.7, 36:00-37:00).
The second feature this timeline makes explicit is that the instructor seemed to set the linguistic expectations and conditions of the learning environment, which students followed. These conditions are evinced by the changes in the named language used by the speakers before and after the white stars on the graph: as soon as the instructor transitioned into using Spanish, Yesenia and Elio followed suit and began using Spanish; the same happened with English. For example, students were using Spanish when they began working individually (Figure 4.7, 6:40) and, at the 10th minute, the instructor asked Yesenia, “which line are you going to start with?”, changing the named language and requesting details about her investigation. Yesenia responded, “the super fat one”, referring to the thickest line she could draw. For the next 15 minutes Yesenia, the instructor, and Elio communicated using linguistic resources associated with English. This monolingual period came to an end when the instructor, once again, transitioned into Spanish, which Yesenia and Elio accommodated to and used Spanish for the next minute, until the instructor switched back to English. Finally, when the instructor used both Spanish and
English, as exemplified by the striped moments (Figure 4.7, 4:10-6:40, 36:00-37:00), students also used Spanish and English for sharing their ideas about electric flow. Thus, the way students followed the instructor’s linguistic lead suggests that they were responding to a shift in the linguistic expectations set by the instructor.

The instructor’s influence on setting linguistic expectations was not limited to the student he interacted with; it impacted all students present. On several occasions, the instructor was interacting with one of the students, he transitioned to using a different named language, and the student sitting across the table also switched to using that same named language. For example, when the instructor asked Yesenia a question in English (Figure 4.7, 10:00), Elio, who was sitting across the table and talking to himself in Spanish as he investigated the circuit, immediately transitioned to speaking to himself in English, despite not being addressed by the instructor. This happened again in the 37th minute of the session, this time transitioning from Spanish into English as soon as he heard the instructor speak English.

**DISCUSSION AND IMPLICATIONS**

In this study, I identified and described the translanguaging practices four emerging bilingual students engaged in when sharing their thinking about electrical phenomena. The first finding, supported by the summary of codes and selected examples, demonstrated that participating students engaged in translanguaging practices throughout the program, leveraging both linguistic and non-linguistic resources when doing so. Specifically, students presented their ideas about the results from their investigations of different electrical phenomena through using linguistic resources associated with different named languages (e.g., Spanish, English), as well as leveraging multiple dimensions of gesturing to illustrate their thinking. However, as the second finding suggests, not all students had similar opportunities for translanguaging during each session, and when they did their translanguaging served different purposes. In particular, Yesenia
and Elio spontaneously transitioned between English and Spanish most often to achieve regulative goals, rather than epistemic ones. The mismatch between Toben and Grace’s semiotic repertoire and the instructor’s might have limited these students’ opportunities for translanguaging to only leveraging non-linguistic resources, like gesturing, which were shared by all participants. The third finding suggests that the instructor set the linguistic expectations of the learning environment, creating opportunities for translanguaging through using specific linguistic resources; these opportunities were available only to Yesenia and Elio, who shared a broader semiotic repertoire with the instructor. In the end, all students were able to collaborate on problematizing electrical phenomena and shared their reasoning through leveraging multiple semiotic resources. After discussing these main findings, I reflect on my own bilingual identity and how it might have influenced instruction, offer some analytical and pedagogical implications, and outline future lines of research.

**Students leveraged multiple semiotic resources when discussing electrical phenomena**

The learning environment acted as a translanguaging space (Wei, 2011), where all four learners relied on multiple resources from their semiotic repertoires for presenting explanations about the electrical phenomena they observed. Yesenia and Elio comfortable used linguistic resources associated with English and Spanish, demonstrating the agency with which they enacted their bilingualism, such as when they constructed an explanation for the battery’s role in an electric circuit (Excerpt 1). At the same time, Yesenia and Elio were able to perform a monoglossic version of bilingualism, captured by the long stretches of time when they used linguistic resources associated with only one named language (see Figure 4.7). This could be advantageous for Yesenia and Elio, given that most K-12 learning environments continue to operate under restrictive language policies (García & Kleyn, 2016; Martínez et al., 2015; Otheguy et al., 2015). Nevertheless, as others have argued (e.g., Espinosa & Herrera, 2016; Poza,
having opportunities to draw on linguistic resources associated with different named languages can be crucial for supporting emerging bilingual students’ participation and co-construction of knowledge.

In addition to linguistic resources, gesturing was a crucial semiotic resource that all students leveraged when sharing their ideas about electrical phenomena. For example, Grace and Toben presented different models for how they thought electricity flowed through a wired circuit, both using gestures to illustrate the path electricity traveled and the sequencing of events (Excerpt 3). These findings address the gap in the literature on how emerging bilingual students rely on gestures when translanguaging for making sense of and communicating about natural phenomena. At the same time, these findings are consistent with other’s work on how gesturing supported monolingual, English-speaking students communicate their ideas about the natural world (Roth, 1996, 2001). Moreover, as investigated in another study (Suárez, dissertation chapter) the tangible experimental tools seemed to support students’ gesturing, particularly by serving as a ground against which gestures could be enacted and disambiguated. Finally, as the literature on gesturing suggests (e.g., Goldin-Meadow, 1999; D. McNeill, 1992), gestures were complementary semiotic resources students used for communicating their explanations of electrical phenomena, rather than ancillary and dispensable. These findings bolster the importance of considering how emerging bilingual students draw from their semiotic repertoires when translanguaging (Blackledge & Creese, 2017; Kusters et al., 2017), especially when making sense of natural phenomena.

It is important to consider that, as discussed above, Toben and Grace did not engage in translanguaging through using linguistic resources from multiple named languages. It is possible that because Toben, Grace, and the instructor only shared linguistic resources associated with
English, these students’ possibilities for translanguaging were limited. And while Toben and Grace still had opportunities to engage in translanguaging by using non-linguistic resources, it is important to interrogate what opportunities for engaging in epistemic practices through translanguaging practices these students might have missed due to the instructor not sharing a similar semiotic repertoire as theirs.

**Students’ translanguaging served different collaborative purposes**

Looking closely at how students engaged in translanguaging when collaborating revealed that students used resources associated with different named languages for different purposes (see Table 4.5). Specifically, Yesenia and Elio, whose linguistic resources were aligned with the instructor, were more likely to spontaneously use resources associated with Spanish for regulative purposes (e.g., managing behavior) than for epistemic purposes (e.g., presenting an idea about electric flow). These findings are consistent with Stevenson’s research (Stevenson, 2013, 2015), where she observed that emerging bilingual Latinx fifth-graders used Spanish when working towards regulative goals (e.g., organizing tasks), while they used English for epistemic ones (e.g., conveying understanding). The differential use of translanguaging practices for achieving specific goals suggests that students were aware of what kind of activity they were engaging in, and chose the semiotic resources they deemed appropriate for participating in that activity; Stevenson (2013, 2015) drew similar conclusions from her research. An example of this awareness is when Yesenia and Elio engaged in translanguaging for both regulative and epistemic goals when preparing a white board with their ideas about the role of the battery, while acknowledging that the final product needed to be in English because it was the only named language they shared with Toben and Grace (Session 4). Perhaps Yesenia and Elio understood that epistemic discourse when presenting their white board was consequential for whole-group discourse, whereas the whole class did not need to be involved in the more regulative discourse.
Some have argued that this kind of awareness is fundamental for students to understand why they engage in certain learning activities (e.g., Berland & Hammer, 2012). However, these findings point to the possibility that, within the context of the science program, Yesenia and Elio did not think that their full semiotic repertoire was appropriate for achieving both regulative and epistemic goals. The learning environment may have driven these two students to enact specific language ideologies, “beliefs, or feelings, about languages as used in their social worlds” (Kroskrity, 2004, p. 498), which constrained the spontaneous use of linguistic resources associated with Spanish for epistemic purposes. These findings highlight the need to attend to the implicit internal and/or external conditions that could keep students from freely using their full semiotic repertoire, and pedagogical strategies to avoid those restrictions.

**The instructor set the learning environment’s linguistic expectations**

The findings also indicate that the instructor set the linguistic expectations throughout the program that students closely followed. Specifically, when the participants only shared linguistic resources associated with one named language (e.g., English), there were less opportunities for students whose semiotic repertoire included linguistic resources associated with other named languages (e.g., Spanish) to engage in translanguaging practices. For example, Yesenia and Elio seldom transitioned between English and Spanish during the sessions where Toben and Grace were present (see Figure 4.5). At the same time, as discussed before, the fact that the instructor only shared resources associated with English with Toben and Grace seems to have decreased their possibilities to translanguage through using linguistic resources associated with Japanese.

This analysis also demonstrated that Yesenia and Elio only used linguistic resources associated with named languages that were similar to those last used by the instructor. These findings resemble the ones reported by Stevenson (Stevenson, 2013, 2015), in which the students’ speech accommodated the named language their teacher and peers used. Moreover,
these results highlight the key role educators play in creating translanguaging spaces where students can use their full semiotic repertoire for participating and learning (García & Kleyn, 2016). On the one hand, if instructors are not attentive to their own translanguaging (or lack thereof), they may set expectations that could restrict students’ use of their semiotic repertoire. A clear example of these restrictions is the case of Grace and Toben, who only used linguistic resources associated with English throughout the whole program, despite being emerging bilinguals. On the other hand, instructors who are committed to supporting their students’ translanguaging practices can create those opportunities through their own translanguaging; mindful instructors may even be able to dismantle the socially-constructed hierarchies that restrict students’ use of their full semiotic repertoire.

Reflecting on the instructor’s bilingual identity and translanguaging practices

As mentioned above, I was the program’s instructor and my semiotic repertoire includes resources associated with both Spanish and English. Unlike the students who participated in the program, who were all developing their bilingual identities and practices as they grew older, my first spoken language is Spanish, and learned English as a second language in my early teens. Moreover, I grew up in a culture in which a monoglossic view of bilingualism is the norm, a perspective that is enacted through belittling those who engage in translanguaging practices, such as Spanglish and “code-switching” (Martínez, 2010, 2014; Urciuoli, 1985). And while I find García’s efforts to bring down the political barriers that buttress separate bilingualism to be liberating, transformative, and necessary, at the same time I often struggle to fluidly leverage linguistic resources associated with different named languages. Therefore, I am constantly experiencing a tension between my commitment to translanguaging and my difficulty of engaging in translanguaging practices myself, especially when teaching.
I experienced this tension during each session of the program, especially when I was spending too much time speaking English, creating few opportunities for Yesenia and Elio to use resources associated with Spanish. This meant that I had to be very intentional about transitioning between named languages, even if I had to force myself out of my linguistic comfort zone. Inevitably, these moments in which I tried to engage in translinguaging were contrived and somewhat haphazard, most visible and apparent in the graphical representation of when named languages were used during Session 8 (see Figure 4.7). I cannot help but wonder what Figure 8 would have looked like had I been more fluent and comfortable coordinating resources from Spanish and English into my speech. Still, I was committed to honoring Yesenia and Elio’s bilingual practices and identities, and creating a space in which they could freely leverage the linguistic resources associated with different named languages and gestures that comprise their full semiotic repertoires. My goal is to continue developing my bilingual identity through these enriching experiences and tensions, leaving behind a monoglossic perspective.

But just as I was committed to Yesenia and Elio’s translinguaging, I experienced another tension throughout the program: what could have I done to also support Toben and Grace’s translinguaging, especially through leveraging linguistic resources? I only shared linguistic resources associated with English with Toben and Grace, and so did the other two students. And, as the analysis shows, Toben and Grace did not engage in translinguaging practices through leveraging multiple kinds of linguistic resources (see Table 4.3, Figure 4.5). I (inadvertently) ensured that, whenever Toben and Grace were present, we all spoke English in order to include them in the activities; this, of course, came at the price of decreasing the opportunities for Yesenia and Elio to engage in translinguaging practices (see Figures 4.5 and 4.6). This raises the question of what translinguaging looks like in multilingual learning environments that include
students who share linguistic resources from only one named language, and how can instructors support all of them to engage in translanguaging practices. Emerging bilingual students are a very heterogeneous group of learners, and it is crucial to account for the similarities and differences in their learning needs when designing equitable learning environments.

Reflecting on analytical decisions

Another tension that arose for me when engaging in this work relates to the analytical decisions I made. Specifically, as stated above, I focused part of my analysis on the exchanges that included transitions between named languages (e.g., Spanish and English), assuming that these were proxies for translanguaging. This decision was pragmatic in nature, given that I could not have access to students’ inner dialogues. Therefore, these transitions between named languages were the only observable evidence I could collect that would indicate that these students were, in fact, leveraging multiple kinds of linguistic resources. However, this analytical decision, in a way, reifies a monoglossic perspective on bilingualism because it continues to treat these linguistic resources as ontologically separate. In fact, the results this analysis yielded could be reduced to “code-switching,” which could obscure the richness with which these students drew from their semiotic repertoires for meaning-making. Fortunately, or perhaps unfortunately, this seems to be a common tension across research on translanguaging in general, in particular those practices that include speakers’ use of linguistic resources. Specifically, researchers focus on identifying and analyzing moments in which speakers transition between named languages, and use those transitions as markers of translanguaging (e.g., Espinosa & Herrera, 2016; Mazak & Herbas-Donoso, 2014; Poza, 2016). At this point is difficult to imagine what the alternative is, especially as we continue to operate in a society that values and upholds a monoglossic perspective of bilingualism, in which true linguistic hybridity is trivialized.
Moving forward

These preliminary findings contribute to our understanding of what translanguaging practices look like in science learning environments, as students engage in productive epistemic practices. As many have argued (Mazak & Herbas-Donoso, 2015; Poza, 2016; Stevenson, 2015), if our goal is to create equitable science learning environments that serve democratic purposes, in which emerging bi-/multilingual students bring their whole selves to the learning process, we need to understand further what are the conditions that support his kind of participation. Moreover, we need educators committed to seeing the full linguistic and cultural repertoire that students bring to science learning environments as assets to be welcomed, valued, and leveraged, rather than deficits that need to be remediated.

With this in mind, there are three main lines of research I would like to pursue further. First, in order to better understand how translanguaging supports’ students conceptual understanding, I would like to analyze in greater depth the moments when students are using linguistic resources from multiple languages when explaining phenomena. Specifically, my goal would be to determine whether the different linguistic resources are associated with or convey information about different aspects a given phenomenon, pointing to a richer and more complex understanding than is represented by only one language. For example, when leveraging resources from Spanish, Yesenia used the verb “estar” to describe what was happening with the electricity as it experienced resistance; when using resources from English, Yesenia used the verb “to be” for the same purpose. And while “to be” and “estar” are technically the translation from each other, the Spanish version of the verb allows the interlocutor to refer to temporal states of being (“ser” refers to permanent states of being), a distinction that is much harder to make when using the English version of the verb. Thus, when Yesenia said, “está más fácil que vaya acá” (Excerpt 2, line 5), Yesenia meant that, at that moment in time and under those conditions, it was easier
for the electricity to move through the thicker line than the thinner one, which may not always be the case. This subtle yet important distinction suggests that Yesenia was aware of the temporal nature of electrical phenomena, rather than thinking of electricity as a permanent steady-state. Leveraging her full semiotic repertoire, then, might have given Yesenia the semiotic tools for making sense of and talking about the nature of electricity in ways that may not have been accessible to her had she been beholden to a monoglossic ideology of bilingualism.

Secondly, I would like to better understand whether different types of activities that students engaged in throughout the sessions (e.g., predicting observations, collecting and interpreting evidence, building explanations) supported translanguaging at different levels. Does asking students to share their explanations create more opportunities for students to use their full semiotic repertoire than, say, planning an investigation? Finally, I would like to investigate in greater depth the co-deployment of semiotic resources, particularly how emerging bilingual students used gestures in conjunction with linguistic resources associated with different named languages, and determine whether some dimensions of gesturing are more like to co-occur alongside specific linguistic resources.
CHAPTER 5

CONCLUSIONS AND IMPLICATIONS

In this final chapter, I summarize the main findings from each individual study and synthesize the main findings and contributions from the overall study. I also discuss possible implications from this dissertation both for learning environments and theory, and offer future lines of research that could further this work.

I set out to describe how emerging bilingual students problematized electrical phenomena through engaging in epistemic practices, and investigate the features of learning environments that could support these students to engage in epistemic practices. As discussed before, emerging bilingual students seldom have opportunities to engage in science epistemic practices due programmatic, pedagogical, and linguistic external constraints. As I will describe below, this dissertation presented detailed accounts of how students engaged in epistemic practices when making sense of electrical phenomena, such as presenting and evaluating mechanistic models of electric flow. Given the complexity of the learning environment, however, it was very challenging to isolate the effects of the design features on supporting emerging bilingual students engage in epistemic practices. Therefore, the findings from these studies offer preliminary insights into design aspects of learning environments that could support emerging bilingual students’ learning and participation.

First, I will highlight the contributions of each individual study. The first manuscript described how four elementary-aged students presented and disagreed about models of electric flow in a circuit. Using a Discourse Analysis approach, I analyzed the transcript of the disagreement, identifying the mechanistic elements students included in their model, as well as the linguistic markers of disagreements students used, leading to three main findings. First, as
demonstrated through the analysis, students’ mechanistic models addressed multiple aspects of the phenomena that they thought were salient. Specifically, students agreed on the different entities (e.g., energy, wires, battery) and conditions (e.g., battery stores energy) that make electricity flow through a circuit. However, they disagreed about two fundamental activities: direction of flow, and what happens to the electricity after disconnecting the battery. These differences created opportunities for students to deeply engage in the epistemic practices of presenting and evaluating mechanistic explanation about what happened to the electricity after disconnecting the circuit. Students carefully attended to and disagreed about the activities that gave rise to their mechanistic explanations, a very sophisticated way of thinking (Russ et al., 2008). And as revealed by the analysis of the linguistic markers students used during their exchanges, students resorted to various linguistic features to present rebuttals, such as questions with markers of negation in them (e.g., “why wouldn’t there be any energy?”), rather than relying on explicit statements of opposition (e.g., “I disagree with you”). While students made clear their disagreement with each other’s models, they enacted these oppositional discursive moves in ways to avoid future or lessen current disagreements, attending to the groups’ social dynamics. Finally, all four students leveraged multiple semiotic resources when sharing and evaluating their peer’s ideas, such as pointing to specific parts of the circuits they were referring to and/or moving their hands to show the path electricity followed as it moved through the circuit, as discussed in study 3.

This first analysis described the rich work these students engaged in when sharing, evaluating, and disagreeing about mechanistic models. For these students, constructing and sharing mechanistic models created opportunities for students to engage in in valuable epistemic practices that are central to science, such as identifying and resolving differences between their
models. Moreover, as the analysis shows, students expressed their opposition towards each other’s mechanistic models through a wide range of linguistic features that indexed opposition. As research on discourse shows, disagreements are often dis-preferred by participants, though (Pomerantz, 1984), a stance that was reflected in students’ discursive moves that tried to decrease the intensity and/or possibility of disagreements about their models. The balancing act between explicit opposition and not being abrasive seemed key for creating and maintaining opportunities for students to continue participating in the process of co-constructing knowledge, rather than turning peers away. These results highlight the importance for educators and researchers to acknowledge how challenging it may be for students to disagree with a peer, or even the teacher, and the need to be intentional about designing low-stakes learning environments where students are supported to present and evaluate explanations through leveraging a wide range of discursive strategies.

In the second study, I explored how distinct sets of tangible experimental tools supported elementary-aged students to problematize electrical resistance, within the context of the designed tasks they were associated with. Specifically, I analyzed portions of the video through coding students’ explicit talk about aspects of electrical resistance (e.g., material composition, length, or width of a resistor), which led to two main findings. The first finding is that, as they engaged with the designed tasks and chosen experimental tools, students problematized conceptual aspects of electrical resistance. As intended by the program’s design, students’ initial models focused exclusively on the conductive nature of the circuit elements, then moved to consider what could obstruct the flow of electricity as an important stepping stone, and their final explanations accounted for how the geometry of the conductive lines affected the transmission of energy. The nature and sequencing of the designed activities, in combination with the distinct
experimental tools, seems to have created opportunities for students to problematize the complexity of electrical resistance. In addition to asking questions about and investigating electrical resistance, students presented and evaluated mechanistic models through leveraging multiple semiotic resources, as detailed in the first and third studies.

The second finding from this study suggests that, within the context of their respective tasks, some of experimental tools introduced affordances for supporting students to problematize electrical resistance. For example, evidence suggests that when students were asked to compare the consecutive lines’ geometry, the CircuitScribe conductive ink made visible how changing the conductive lines’ length and width affected how much electricity flows through the circuit. At the same time, some of these experimental tools presented some important constraints within the design of the program. For instance, it would have been challenging to design an activity to investigate intensive and extensive properties of electrical resistors using the chosen insulators (e.g., fabric) and conductors (e.g., penny), since these objects’ physical and chemical properties could not be altered easily. Additionally, students never quite developed fluid skills for manipulating the conductive ink, making it difficult for them to draw circuits without targeted interventions from the instructor to show students how to work with these experimental tools. This difficulty may be a product of how far removed drawing circuits was from connecting wires, making drawing circuits with the CircuitScribe conductive ink not intuitive for students.

This study contributes to the small body of literature on how elementary-aged students make sense of electrical resistance in greater sophistication than the insulator/conductor binary. Specifically, it describes how these students proposed models that described electrical resistance as an obstacle for electricity, and later accounted for the resistor’s geometry as regulating how much electricity flowed through. Moreover, this study described a series of design decisions,
specifically the kinds of tasks and experimental tools used, which seemed to have supported these students in problematizing the complexity of electrical resistance. Finally, as they moved through the activities in the program, the emerging bilingual students engaged in various epistemic practices, often by leveraging multiple semiotic resources. Particularly, as they investigated electrical phenomena, these students presented their mechanistic models about electric flow, and evaluated and negotiated differences between their models, all the while transitioning between named languages and/or using gestures to illustrate their thinking.

The third study described how the four elementary-aged, bilingual students engaged in translanguaging practices when sharing their ideas and reasoning about electrical phenomena, through leveraging named languages and/or gestures. For this study, I coded all the exchanges in which students transitioned between named languages (e.g., Spanish and English) and/or used different dimensions of gestures, categorized how these translanguaging practices served different collaborative functions, and identified possible instructor moves that seemed to support students’ translanguaging. The first finding, supported by the summary of codes and selected examples, described how students engaged in translanguaging practices when presenting and evaluating mechanistic models of electric flow and electrical resistance, leveraging both linguistic and non-linguistic resources when doing so. The second finding suggests that not all students had opportunities to engage in translanguaging during each session, and when they did their translanguaging served different purposes. The third finding details how the instructor set the learning environment’s linguistic expectations, which seemed to have created translanguaging opportunities for students.

These findings contribute to our understanding of what emerging bilingual students’ translanguaging practices could look like in science learning environments, as students engaged
in epistemic practices. As many have argued, if our goal is to create equitable science learning environments that serve democratic purposes, in which emerging bi-/multilingual students bring their whole selves to the learning process, we need to understand further what are the conditions that support his kind of participation. Furthermore, if we frame science learning as a set of dynamic cultural processes based on how people make sense of the natural world in ways that are connected to the practices, values, and languages of their communities (Bang et al., 2012; Gutiérrez & Rogoff, 2003), then equitable learning environments for emerging bilingual students need to offer opportunities for heterogeneous meaning-making (Rosebery et al., 2010), which includes engaging in translanguaging practices. Consequently, we need educators committed to seeing the full linguistic and cultural repertoire that students bring to science learning environments as assets to be welcomed, valued, and leveraged, rather than deficits that need to be remediated.

**Implications for Theory**

The findings and conclusions from this dissertation make three contributions to how science education researchers understand the learning of elementary-aged emerging bilingual students. The first main contribution is a detailed account of how emerging bilingual students engaged in epistemic practices to problematize electrical phenomena. Most research on how emerging bilingual students learn science has focused predominantly on the kinds of language resources that need to be included in learning environments to support their learning (Brown & Ryoo, 2008; Buxton, Lee, & Santau, 2008; Lee & Buxton, 2008; Warren et al., 2001). And, while more research is needed, throughout the program, emerging bilingual students presented mechanistic models about electric flow, and identified and negotiated disagreements between their reasoning. Moreover, as they moved through the activities, emerging bilingual students developed more complex models of electrical resistance that went beyond the traditional insulator/conductor
binary taught by most elementary-level science curricula. The program’s design, intent on creating opportunities for students to investigate multiple aspects of electrical phenomena, seems to have supported the enrolled emerging bilingual students to engage in epistemic practices, as they participated in intentionally designed and sequenced activities. These findings push us to consider the features of the science learning environment we can design in order to create opportunities for emerging bilingual students to learn science by doing science.

The second contribution to theory from this dissertation is that learning environments need to create opportunities for emerging bilingual students to engage in productive epistemic work through leveraging multiple kinds of resources from their semiotic repertoires. Elio and Yesenia transitioned back and forth between English and Spanish when discussing the role a battery played in a circuit, and deciding how to represent those ideas for sharing with Toben and Grace. Toben proposed that electricity flowed from the battery through each wire until it reached the lamp, but asynchronously, which he illustrated through pointing to different parts of the circuit and moving his hands to illustrate the electricity’s path and timing. Students engaged in translanguaging practices through drawing from their semiotic repertoires as they problematized the electrical phenomena they observed.

Finally, this dissertation contributes to our understanding of how emerging bilingual students engage in translanguaging practices as they investigate and make sense of the natural world. So far, most of the research has focused on developing emerging bilingual students’ skills in writing and reading about science (Espinosa & Herrera, 2016; Mazak & Herbas-Donoso, 2014; Poza, 2016; Stevenson, 2013, 2015). While reading and writing are important for presenting and evaluating ideas about the natural world, these studies offer little information about what role translanguaging plays as students engage in other aspects of science disciplinary practices. This
dissertation offers detailed insight into how, under the right conditions, students leverage linguistic and non-linguistic resources for problematizing natural phenomena. Specifically, the third study illustrated how the instructor can set linguistic expectations of the learning environment, creating trans languaging opportunities for students. Therefore, these studies highlight the need to understand further how educators shape the opportunities available for students to engage in trans languaging practices, especially if our goal is to create equitable learning environments in which emerging bilingual students can leverage their conceptual and communicative resources for problematizing the natural world.

Implications for Learning Environments

In addition to theoretical implications, this dissertation offers various contributions for elementary-level science learning environments. Before presenting the implications, however, it is important to acknowledge again that this study was conducted within an out-of-school-time setting, in which I had complete latitude for designing and implementing the program. Such flexibility stands in direct contrast to the very real logistical and programmatic demands and constraints of in-school-time science learning environments. As such, while I argue that these studies’ findings can provide useful insight for the teaching and learning of science in the elementary grades, particularly with emerging bilingual students, I also recognize that the implications I discuss below would need to be adapted in order to fit specific K-5 classrooms.

As science educators, it is important for us to recognize, value, and leverage the ways in which emerging bilingual students make sense of and engage in epistemic practices of the discipline. While we may have our own expectations for how emerging bilingual students should make sense of the natural world, such as enacting each of the eight practices outlined in the framework for K-12 science education (National Research Council, 2012), our science learning
environments need to create opportunities for these students to engage in epistemic practices through leveraging their conceptual and communicative resources. As the studies presented here show, the emerging bilingual students in the program engaged in rich and productive epistemic work, the type of work that is often unexpected of students their age. For example, as described in the first study, students disagreed about each other’s mechanistic models of electric flow through a circuit in ways that went beyond the expected overt opposition (e.g., “I disagree with…”). In fact, students often used discursive strategies to signal their opposition to their peers’ reasoning, while simultaneously mitigating or avoiding conflict. These results highlight how important it is for educators to recognize that supporting students to engage in argumentation also requires attending to why a student may be reluctant to explicitly and intensely disagree with a peer. As science educators, we risk missing a great deal of productive and rich talk about ideas and reasoning if we value a limited set of ways to enact disagreements. Constraining what counts as a productive disagreement may create conditions and expectations that could, inadvertently, alienate students from meaningfully participating in the process of co-constructing knowledge.

Especially if our intention is to design equitable science learning environments where emerging bilingual students develop conceptual understandings of natural phenomena, it is imperative that we understand how to support these students’ learning through leveraging their complex semiotic repertoires. The findings from these studies suggest that the designed and sequenced activities created opportunities for students to problematize phenomena and share their thinking, sometimes by engaging in translanguaging practices. For example, Yesenia and Elio were able to fluidly transition between English and Spanish when making sense of and talking about the various electrical phenomena they observed. In a way, they were able to access
a broader semiotic repertoire from which they could choose different communicative resources that allowed them to efficiently share their thinking, such as when explaining how the thickness of a conductor affects electric flow. Similarly, Toben and Grace engaged in translanguaging practices through using multiple dimensions of gestures, such as when they shared their models about electric flow while gesturing to and about different parts of the circuit. Had the learning environment and the instructor prohibited students from sharing their thinking through these communicative strategies, it is possible that students would have not been able to participate in the co-construction of knowledge. Moreover, without these communicative strategies, it would have been nearly impossible for the instructor to assess these students’ reasoning and make pedagogical decisions to support their learning.

Future Research

The findings and conclusions from the studies in this dissertation are only the first steps in an extensive line of research. Related to the first study, there would be two main research questions I would pursue further. First, it would be important to further investigate what aspects of students’ disagreements about the flow of electricity through a circuit were explicit, and which ones were implicit. The answer to this question will be useful for understanding whether different types of activities create different opportunities for students to identify, articulate, and negotiate differences in their reasoning, as well as affect the explicitness of their disagreements. Additionally, I would like to investigate how similar patterns emerge between students in a different learning environments, particularly with respect to the linguistic features included in and explicitness of their disagreements. Findings from this investigation could provide further insight into the how interpersonal aspects of disagreements (e.g., mitigating conflict) affect how students present and evaluate ideas about the natural world. It is possible that different groups could develop their own idiosyncrasies when it comes to enacting disagreements between
students, which would continue to increase the richness of our understanding of what disagreements look like in elementary-aged science learning environments.

With respect to the second study, one future line of research I would like to pursue is understanding in greater depth how exactly the tangible experimental tools could support students to problematize different aspects of electrical resistance. This study described and articulated how the combination of the investigations tasks and the experimental tools created opportunities for students to problematize electrical resistance. However, given the program’s design, it was impossible to disentangle the effects of the experimental tools from the task context students used them in. Further research on the affordances and constraints of specific experimental tools can help the selection of more appropriate tools for problematizing electrical resistance, in relation to specific investigations. Additionally, I would like to investigate further how students coordinate their findings from investigations on how intensive and extensive properties of resistors affect electric flow, into a single coherent mechanistic model of electrical resistance. Finally, while this study’s results will inform future iterations of the program in an out-of-school-time learning environment, eventually my goal would be to bring this design to K-5 classrooms; most likely to 3rd or 4th grade, when electrical circuits are reviewed.

Related to the third study, there are two research questions I would like to investigate further. First, I would like to better understand whether different types of activities that students engaged in throughout the sessions (e.g., predicting observations, collecting and interpreting evidence, building explanations) supported translanguageing at different levels, both in terms of frequency and nature of the students’ translanguageing practices. Does asking students to share their explanations create more opportunities for students to use their full semiotic repertoire than, say, implementing an investigation? Finally, I would like to understand how to create opportunities
for emerging bilingual students to engage in translanguaging practices during school-time science learning, especially in classrooms with a heterogeneous linguistic makeup where the instructor may share a named language with a small portion of the students.
REFERENCES


Specific Subjects. Washington, DC.


Appendix A: Summer 2016 Lesson Plans

Session 1 – Plan

Building Circuits with Cables

Driving Question:
How is it that using these batteries and cables makes the lamp turn on?

Goals:
1. Getting to know each other
2. Investigating how electricity flows through a circuit
3. Proposing a common model for how electricity flows through a circuit

Materials:
- Incandescent Lamps
- D Batteries + Holders
- Alligator Cables
- Resistors
- Markers + Whiteboards (small and big)

Procedures:
1. Icebreaker: (10 mins) “Name Relations Game” – First person says their name and a food that starts with first letter; the next person does theirs, plus yours, and so on.
2. Partnering: (2 mins) Pair students. “[Name] will be your partner for the summer”
3. Electricity?: (5 mins) “What do you know about electricity? Talk to your partner” Share out.
4. Introduce investigation: (10 mins) “Today we’re going to be working with cables, batteries, and light bulbs, and explore how is it that using these batteries and cables makes the lamp turn on (SHOW MY SET). Before we get started, with your partner, I would like for you to write/draw: What do you think is going to happen and why. If you don’t agree with each other, that’s fine; write/draw all of your ideas.” Share out and write predictions on board. “How do you think we should investigate this question?” Share out and write on the board.
5. Investigation: (15 mins) Pass around materials. “You can also use these whiteboards to show your thinking.” Share out observations. “Please put all of your materials back in the containers.”
6. Defining Explanatory Model: (5 mins) “What do you think makes a good explanation?” “I liked the way you…” “Our goal is to come up with a common model to explain our observations. What do you think when you hear the word model? What do you think makes a good model? (It should show the process of what happened).”
7. Building a Common Model: (15 mins) “In your white boards, draw a model that shows how and why the lamp turns on.” “Which group would like to tell us what you think is making the lamp turn on?” (Talk Moves!) “What is similar/different? What would a common model look like?”
8. **Wrap-up**: (5 mins) “What was one thing you learned today?” Go around. “Next week we’re going to continue investigating what makes the lamp turn on, but we’re going to be using something different.”

**Session 2 – Plan**

**Explaining how circuits work**

**Driving Question:**
How is it that using these batteries and cables makes the lamp turn on?

**Goals:**
1. Getting to know each other
2. Investigating how electricity flows through a circuit
3. Proposing a common model for how electricity flows through a circuit

**Materials:**
- Incandescent Lamps
- D Batteries + Holders
- Alligator Cables
- Resistors
- Markers + Whiteboards (small and big)

**Procedures:**
1. **Recapping**: (10mins) “What did we do last time? What did you learn? Talk to your partner”
2. **Introduce investigation**: (10mins) “Today, we’re going to try to figure out how we can use these cables and this battery to make the lamp turn on.” Say more about working in groups and finding as many ways as possible to make it light up. “How do you think we should record our observations?” Share out and write on the board.
3. **Investigation**: (20mins) Pass around materials. “You can also use these whiteboards to show your thinking.” Share out observations. “Please put all of your materials back in the containers.”
4. **Defining Explanatory Model**: (5mins) “What do you think makes a good explanation?” “I liked the way you…” “Our goal is to come up with a common model to explain our observations. What do you think when you hear the word model? What do you think makes a good model? (It should show the process of what happened).”
5. **Building a Common Model**: (10mins) “In your white boards, draw a model that shows how and why the lamp turns on.” “Which group would like to tell us what you think is making the lamp turn on?” (Talk Moves!) “What is similar/different? What would a common model look like?”
6. **Wrap-up**: (5mins) “What was one thing you learned today?” Go around. “Next week we’re going to continue investigating what makes the lamp turn on, but we’re going to be using something different.”
Session 3 – Plan

Drawing Circuits with Conductive Ink

Driving Question:
How is it that we can use ink to draw a circuit that works (e.g., lights, sound, motion)?

Goals:
1. Investigating how electricity flows through a circuit
2. Revising models for how electricity flows through a circuit
3. Begin conceptualizing conductivity of substances

Materials: (5-6 kits)
- Conductive Pens
- 9V battery + Adapter
- 2-pin Adapter + Incandescent lamp
- Components: Bi-directional LED; Buzzer; Fan
- Drawing Stencil
- Markers + Whiteboards (small and big)

Procedures:
1. Recapping model: (10mins) “What did we do last time? What did you learn? Talk to your partner” “On this big whiteboard, let’s draw the rule for how we could make the lamp light up.” “How should we call this thing? (point to the drawing of the circuit)”
2. Introduce exploration: (5mins) “Last time we were using cables like these to make the lamp light up. This week, we’re going to try something different: we’re going to be using these pens to make the lamps, and other components, work.” Show all of the different components in their kits and point to the labels. “You can use this template to help you draw the connections. Notice that the components stick to the small boards.” “You will have a lot of time to explore drawing with the pen, and keep track of what you observe.”
3. Exploration: (15mins) “How do you think we should record what we see?” Share out and write on the board. “You can also use these whiteboards to show your thinking.”
4. Explaining your observations: (10mins) “Please put all of your materials back in the containers. Now it’s time for us to think about what we saw when drawing the connections, and come up with ideas that explain our observations.” “As you are explaining your observations, think of what questions you may have about the connections you drew.”
5. Share out observations and explanations: (10mins) “On this large piece of paper, write and/or draw everything you saw happen when you were drawing the connections.” Table: Groups; Observations; Explanations
6. Building a Common Model: (10mins) “Let’s come up with a common explanation for how and why the lamp turns on.” “Which group would like to tell us what you think is making the lamp turn on?” (Talk Moves!) “What is similar/different? What would a common model look like?”
7. Wrap-up: (maybe intro to session4) “Why do you think the pen worked just like the cables?”
Session 4 – Plan

Drawing Circuits with Conductive Ink

Driving Question:
How is it that we can use ink to draw a circuit that works (e.g., lights, sound, motion)?

Goals:
1. Investigating how electricity flows through a circuit
2. Revising models for how electricity flows through a circuit
3. Begin conceptualizing conductivity of substances

Materials: (5-6 kits)
- Incandescent Lamps
- D Batteries + Holders
- Alligator Cables
- Conductive Pens
- 9V battery + Adapter
- 2-pin Adapter + Incandescent lamp
- Components: Bi-directional LED; Buzzer; Fan
- Drawing Stencil
- Markers + Whiteboards (small and big)

Procedures:
1. Recapping previous session: (5 mins) “What did we do last time? What did you learn? Talk to your partner” (look for: activation of components, orientation/matching made a difference).
2. Introduce exploration: (3 mins) “Last time we were the ink in these pens to make the lamps, and other components, work. You seemed very close to coming up with a way of connecting the battery and the components with ink. I will give you another 5 mins for you to complete your ideas. The goal for today is to come up with as many working connections as we can, and then explaining how and why the components worked.”
3. Exploration: (20 mins) [if necessary, show how I would complete a working circuit] “I would like for you to record what you are seeing at the top of this sheet. How do you think we should record what we see?”
4. Explaining your observations: (5 mins) “Please put all of your materials back in the containers. Now it’s time for us to think about what we saw when drawing the connections, and come up with ideas that explain our observations.” “As you are explaining your observations, think of what questions you may have about the connections you drew. One group is going to present their explanation on the board, and the other group will agree, add, and/or modify the other group’s explanation.”
5. Building a Common Model: (20 mins) “Let’s flip a coin and decide who will begin by presenting their explanation. The goal is for us to come up with a common explanation.”
“On this large, write and/or draw everything you saw happen when you were drawing the connections and an explanation for how and why the lamp turns on.”

Wrap-up: (maybe intro to session4) “Why do you think the pen worked just like the cables? What is similar/different? What would a common model look like?”

Session 5 – Plan

**Drawing Circuits with Conductive Ink**

**Driving Question:**
How is it that we can use ink to draw a circuit that works (e.g., lights, sound, motion)?

**Goals:**
1. Investigating how electricity flows through a circuit
2. Revising models for how electricity flows through a circuit
3. Begin conceptualizing conductivity of substances

**Materials: (5-6 kits)**
- Conductive Pens
- 9V battery + Adapter
- 2-pin Adapter + Incandescent lamp
- Components: Bi-directional LED; Buzzer; Fan
- Drawing Stencil
- Markers + Whiteboards (small and big)

**Procedures:**
1. Recapping model: (5mins) “What did we do last time? What did you learn? Talk to your partner”
2. Introduce exploration: (5mins) “Last time we were using cables like these to make the lamp light up. This week, we’re going to try something different: we’re going to be using these pens to make the lamps, and other components, work.” Show all of the different components in their kits and point to the labels. “You will have a lot of time to explore drawing with the pen, and keep track of what you observe.”
3. Open Exploration: (10mins) [Pass around kits and tell students to explore what each of the parts does]. “As you explore the kit, I want you to think about how you could use the ink in this special pen to make a connection that works.”
4. Guided Exploration: (15mins) “You can use this template to help you draw the connections. Notice that the components stick to the small boards.” Pass around printouts. “How do you think we should record what we see?” Share out and write on the board. “You can also use these whiteboards to show your thinking.”
5. Explaining your observations: (10mins) “Please put all of your materials back in the containers. Now it’s time for us to think about what we saw when drawing the connections, and come up with ideas that explain our observations.” “As you are explaining your observations, think of what questions you may have about the connections and the ink.”
Session 6 – Plan

**Driving Question:**
Why is it that the lamp turns on when we add some objects to the circuit, but not with others?

**Goals:**
1. Investigating how electricity flows through a circuit
2. Revising models for how electricity flows through a circuit
3. Begin conceptualizing conductivity of substances

**Materials:** (5-6 kits)
- Conductive Pens
- 9V battery + Adapter
- 2-pin Adapter + Incandescent lamp
- Components: Bi-directional LED; Buzzer; Fan
- Drawing Stencil
- Markers + Whiteboards (small and big)

**Procedures:**
1. **Recapping previous session:** (5 mins) “What did we do last time?” [listen for: activation of components, orientation/matching, how to draw circuit]. “Why do you think the pen worked just like the cables? What is similar/different?”
2. **Introduce exploration:** (3 mins) “Last time we were the ink in these pens to make the lamps, and other components, work. True mentioned that the ink worked because it was special ink. A metal ink. So, today we’re going to figure out which objects are good for making the lamps light up, and explain why some objects work and some don’t. The way we’re going to do this is by change part of the ink with different objects and test them. How do you think we could test which objects work, using the ink the way we have before?” [if necessary, show how I would complete a working circuit]
3. **Exploration:** (20 mins) “I have given you different objects that I want you to test and determine whether they can make the components work. You can choose to use the lamp, the buzzer, or the fan to test the objects.” [show the objects and point them out on the printout]. “Also, I would like for you to record what you think is going to happen, what you are observing, and explain why the objects work or don’t work.”
4. **Explaining your observations:** (10 mins) “Please put all of your materials back in the containers. Now it’s time for us to think about what we saw when testing the different objects, and come up with a rule for which types of objects work and why.” [groups share their thinking]

**Building a Common Model:** (20 mins) “It sounds like you all agree that it’s only the metal objects that make the components work. We should now explain in detail what’s happening inside the metal and what’s happening inside the non-metals that makes the components work. On this large paper, please write and/or draw what you think is happening that make some work.” [set up large paper, divide it into metal/non-metal, a group for each, then switch]

**Session 7 – Plan**

**Which objects complete the circuit & Length of the line**

**Driving Question:**
Would it make a difference if we make the lines of ink longer or shorter?

**Goals:**
1. Investigating how electricity flows through a materials/objects
2. Conceptualizing conductivity of substances
3. Investigate how/why length of the line makes a difference

**Materials: (5-6 kits)**
- Conductive Pens
- 9V battery + Adapter
- Components: Bi-directional LED; 2-pin Adapter + Incandescent lamp
- Drawing Stencil
- Sketch Paper
- Markers + Whiteboards (small and big)

**Procedures:**
1. **Recapping previous session:** (5 mins) “What did we do last time?” [listen for: not all objects worked, metals worked].
2. **Building Model of Resistance:** (20mins) “Why do you think only metals worked? We should now explain in detail what’s happening inside the metal and what’s happening inside the non-metals that makes the components work. On this large paper, please write and/or draw what you think is happening that make some work.” [set up large paper, divide it into metal/non-metal, a group for each, then switch].
3. **Introduce exploration:** (5 mins) “Why do you think the pen worked just like the cables? What is similar/different?” [time to discuss here a bit] “Last time we were the ink in these pens to make the lamps, and other components, work. A couple of weeks ago Yesenia mentioned that the longer lines wouldn’t work as well. So, Today we’re going to test Yesenia idea and see if the length of the line makes a difference. How do you think we could test of the length of the line makes a difference?”
4. **Exploration:** (20 mins) “The goal for today is for you to draw at least 5 lines of different lengths, see if there’s a difference in how the lamps work, and explain what’s going on. I would like for you to record what you think is going to happen, what you are observing, and explain your observations.”

5. **Explaining Length:** (5 mins) “Please put all of your materials back in the containers. Now it’s time for us to think about what we saw when testing different lengths and come up with a rule for how the length makes a difference. You will have 5 minutes to come up with an explanation that you will present to the other group. Why did the length make a difference?”

6. **Building Model of Length:** (5 mins) [one group presents their thinking on the paper and the other group reacts]

**Session 8 – Plan**

**How does the width of the line affect the electrical flow**

**Driving Question:**
Would it make a difference if we make the lines of ink thicker or thinner?

**Goals:**
1. Investigating how electricity flows through a materials/objects
2. Investigate how/why width of the line makes a difference

**Materials:** (5-6 kits)
- Conductive Pens
- 9V battery + Adapter
- Components: Bi-directional LED; 2-pin Adapter + Incandescent lamp
- Drawing Stencil
- Sketch Paper
- Markers + Whiteboards (small and big)

**Procedures:**
1. **Recapping previous session:** (5 mins) “What did we do last time?” [listen for: not all objects worked, metals worked].
2. **Introduce exploration:** (5 mins) “Last time, Grace noticed that the longer the line, the less electricity would make it to the lamp. She explained what was happening using a tub and suds bubbles. But we were left with the question: what is the tub is wider? Would it still make a difference? So, today we’re going to answer Grace question and see if the width of the line makes a difference. How do you think we could test of the width of the line makes a difference?”
3. **Exploration:** (15 mins) “The goal for today is for you to draw at least 5 lines of different widths, see if there’s a difference in how the lamps work, and explain what’s going on. I would like for you to record what you think is going to happen, what you are observing, and explain your observations.”
4. **Explaining Width:** (15 mins) “Why did the width make a difference? We should now explain in detail what’s happening inside the metal to where the width of the line is affecting how much electricity makes it to the lamp.”

5. **Building Model of Resistance:** (20mins) “On this large paper / white board, please write and/or draw what you think is happening that explains how/why the length and the width make a difference for how much electricity makes it through to the lamp.”