Multimodality and Learning: Exploring Concept Development and Student Engagement in a Physics Classroom

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THESIS
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SUMMARY

The purpose of this study was to investigate how different modes of communication used in a 9th grade physics class during an instructional unit on waves benefit and/or limit students' conceptual development and engagement with each other in the context of particular learning activities. I was both the teacher and active participant in the community and multimodal discourse that I was studying, and the researcher who analyzed this multimodal discourse. I examined one of my ninth grade honors physics classes throughout a 12-day instructional unit on waves during the second semester of a school year, espousing a sociocultural perspective of learning. In this perspective, engagement with scientific ideas in a class is mediated by multimodal communicative acts between teacher and students and among students themselves. Moreover, consideration for all three metafunctions of any communicate act–ideational, interpersonal, and textual–is imperative for supporting conceptual development..

Using ethnographic and grounded theory techniques, I examined how my students and I called upon different modalities–our interactions within and about modes, the semiotic features and grammar of a mode, and the potential affordances, limitations, and challenges that modalities offered to student learning and engagement. Data were collected via videotaping all 12 50-minute lessons on waves. In addition, immediately after each lesson, I wrote teacher-researcher reflections on noteworthy events, as well as my thoughts, comments, observations from that day's class, especially with regards to the goal of this study. After instruction was completed, I reviewed all of the video and reflection data, and constructed sketches–outlines describing the events that occurred, as well as noting interpretative comments regarding those events. My interpretations revealed general trends and themes over the course of the unit as well as more specific critical moments in the multimodal discourse that warranted a closer and more delicate analysis. This led to new ways of looking at the data, combining and recombining interpretations and themes.

Two modes emerged as prevalent: gesturing and diagramming. Gesturing, and in particular iconic hand gestures, was a prominent and consistent mode for meaning making among class participants and its meaning evolved over time as my students and I used this mode. There were two primary iconic gestures used in my classroom: an undulating hand gesture (UHG) and a back and forth hand gesture (BFG). These hand gestures served as teaching and learning tools as I helped students construct meaning of wave characteristics such as amplitude, period, and frequency, as well as the sinusoidal propagation of waves.

As gestures evolved in both form and function throughout the unit, so did students' conceptual understandings. The UHG embodied students' drawings on the first day of the unit, and developed over time particularly as students engaged with the sinusoidal shape of waveform graphs. The BFG stemmed from students' experience producing waves in a slinky during their experiments. As students used the BFG in relation to waveform graphs, which had a sinusoidal shape, the BFG acquired an undulating characteristic as students shifted from simply shaking their fist back and forth to tracing, in air, the sinusoidal shape of a graph's curve. This combination of the BFG with the UHG mediated students' linking the wavy nature of the graph depicting wave propagation (in UHG) with the back and forth motion of the wave source and the medium's particles (in BFG).

In addition to gesturing, the development of diagrams as a prominent modality for meaning making took place as my students and I continuously diagrammed across activities. The specific forms of diagrams used and the ways in which they functioned to provide my students

opportunities for meaning making constituted the diagrammatical grammar that my class explored. There were several critical characteristics of the diagrammatical grammar that my students and I co-constructed over the instructional unit, including: iconic depictions of artifacts, selection of critical instances to capture, artifact positioning and manipulation, representation of measured values or variables using arrows and brackets, and textual labels or captions. When diagramming a context, students had to select an instance or instances to depict. Students' ability to choose these instances reflected an understanding of how to analyze and simplify an event in order to explain it in more detail. The act of diagramming created epistemological affordances for students to analyze particular instances, and consider details at those particular instances in which they might not have otherwise engaged with and/or fully represented. Using diagrams, my students constructed an individual and collective understanding of not only *what* aspects of a phenomenon or event were important to depict, but also *how* to utilize semiotic resources to represent them in diagrams. Thus, diagrams influenced the conceptual development, or ideational engagement, of my students, in addition to offering me a window into their understanding at a particular instant.

In addition to the salience of gesturing and diagramming, the study offered understandings regarding the evolution of two major thematic patterns across various modes– understanding and measuring wave characteristics; and learning about relationships between various wave characteristics from experimental data. Regarding wave characteristics, transduction and combination of modalities offered new and various opportunities for meaning making, and students' conceptual understanding shaped students' engagement with different modalities. Transduction between modes helped students develop concepts, such as the period of a wave. The idea began as a brisk BFG as a referent to wave production, but functioned as a multimodal scaffold to students' developing the concept of period within the diagrammatical and graphical modes. The *sequence* of transduction among modes was also integral to the teaching and learning of wave characteristics. When I transformed a photograph of a wave in a slinky into a graph by drawing axes, and thus creating a combination of three modes–photograph, diagram, and graph–various meanings became possible by the co-existence of the various modes.

Students' choice of which modality or modalities to engage with, how to utilize the grammar of those modalities, and to transduce between modalities, were all integral to their understanding of relationships among wave characteristics, as well as how to derive them from experimental data. Students engaged with numerical data arranged into tables and plotted them on graphs via computer software and free-hand sketches in order to determine relationships among wave characteristics. The units of quantitative measurements in a table mediated a link between numerical values and other modalities such as diagrams and graphs that may or may not have quantitative features. Moreover, examining data while being collected, as opposed to at end of data collection, afforded students more meaning-making opportunities. As students interpreted their data during data collection, they were able to identify possible patterns and infer expectations, and then test their expectations as they continued to collect data.

There was also a significant interplay between tables and graphs as students extrapolated relationships from data sets. Tables afforded students the opportunity to view data as individual points, and calculate a value for error that could also be used to differentiate between covariant and non-covariant trends in their data. However, tables did not easily allow students to identify the particular covariant relationship, and could not provide quantitative information about the

relationship, such as regression values. A key to students' success in understanding relationships among wave characteristics was the sequence of their transduction between modes. Students who first engaged with tables, which emphasized data as individual points, avoided a potential point of confusion that arose from computer-generated graphs, which reduced the level of inference that the tables afforded. The computer-generated graph represented the empirical relationship within a graphical mode that allowed students to create a free-hand graph with little engagement with the underlying relationship. In contrast, a free-hand graph of the empirical relationship represented in a table forced students to first infer its shape (or relationship) in light of their analysis of the individual values in the table before graphing it using the computer software.

In general, as students developed conceptual understandings using different modalities, they also developed their abilities to make meaning and articulate ideas using those modalities. Students' conceptions of the grammar (form and function) of a particular mode were co-developed together with both the concepts and ideas, and the grammars of other modes. Each mode did not develop meaning in isolation from each other; instead, the intertwining, transduction, combination, and hybridization of modes offered powerful opportunities for meaning making. As students appropriated, shared and articulated multiple ways for multimodal communication of ideas related to these concepts, they became better able to explicate and developed multimodal understandings of those concepts. Ideational development was achieved interpersonally through multiple modalities, each of which carried syntax and semantics that constituted its grammar. Just as ideas change through discursive interactions and practices, so do the interpersonal and grammatical practices used to negotiate and shape them.

As students transduced among modalities, each mode afforded unique meaning-making opportunities that contributed to the collective meaning and the development of the idea. However, the sequence of students' transduction represented a learned practice that they developed discursively throughout the unit. Moreover, they demonstrated an understanding by choosing an appropriate modality for a particular situation, and how to build upon the meanings developed from prior modalities. The students in my class converged upon a particular order of transduction from data tables to graphs that enabled them to derive empirical relationships that agreed with the scientifically accepted ones, and more specifically to successfully differentiate between covariant and non-covariant trends. Students who engaged with data tables before generating graphs using a computer program were able to engage with graphs in more meaningful ways.

Students' engagement with one mode influenced the ways in which they called upon and utilized other modes, and in some cases, modes combined while retaining their individual grammars (combination), or blended together into new modes with their own grammar (hybridization). The meaning associated with undulating hand gestures and back and forth hand gestures transformed as they were synthesized into a single gesture, which afforded students the ability to produce iconic gestures of non-observable propagation of waves. The superposition of multiple modes allowed for a diagram I drew to better connect to a reality captured by a photograph, while abbreviating its myriad details to only those I considered important and depicted in my diagram. My diagram's characteristics also resembled graphical features, which further transduced the diagram-photo combination to a waveform graph. The superposition and combination of the modes allowed students to consider waveform graphs with which they were previously unfamiliar, in light of the other modes that were more familiar to them. This promoted the retention and utilization of those modes since each mode still existed while a new mode was superimposed onto it. Moreover, Free-hand graphs, which were a prevalent modality used by students, were a hybrid of diagrams and graphs. When a diagram of a graph was constructed, graphical features such as axes and best-fit lines also became diagrammatical characteristics. A free-hand graph's characteristics combined the brevity of a diagram with the graphical concept of prominence of the relationship between independent and dependent variables.

The findings of this study suggest several implications for practice. Availability and access to multimodality is critical to creating a multimodal discourse in the classroom. Omnipresent multimodal spaces in which students may call upon whichever mode they prefer or deem necessary is of particular importance. In addition to available multimodal spaces, students need to develop the grammar of each mode in order to gain confidence and strengthen their initiative to both call upon and engage with modes effectively, which will in turn promote those modes as prominent and effective ways of constructing and negotiating meaning.

Thus, a teacher should aim at promoting students' use of various modes by continually providing students with multimodal spaces and by modeling for them the grammars of modalities. It is also important for students to model grammatical practices for each other. During any form of communication, students are demonstrating grammatical aspects of the mode(s) they use. These aspects may already exist in the class's collective grammar for that mode, or may be new ones created by a student based on the needs or motivations for communicating in that mode.

Since transduction among modes is critical to teaching and learning via multimodality, a teacher's careful planning and consideration of the sequence of transduction among modes is especially important. Teachers need to be particularly adept in recognizing, and reversing, student inability to transduce between modes. Such an inability may be due to a compromised understanding of an idea, or lack of knowledge of the grammars of the modalities to be transduced, or a combination of the two.

Students' multimodal engagement with science ideas and the role that grammars of modes play in constructing meaning represent potentially fruitful areas for future research. There is little research in science education that explores the development of both teaching and learning via multimodality; that is, how both teacher and students multimodally develop their ideas together. The practices of transformation and transduction, and combination and hybridization of modalities, are particular areas in need of further research. The many possible ways in which modalities blend together into combinations or new hybrid modes during teaching and learning, and the circumstances and motivations that lead to such combinations are largely unknown. Furthermore, teacher research, which was the methodological approach of this study, can provide unique opportunities and perspectives to important areas of research in science education, including but not limited to multimodality.

I. INRODUCTION AND RESEARCH QUESTION

The purpose of this study is to investigate how different modes of communication used in a physics class during an instructional unit on waves might benefit or limit students' conceptual development and engagement with each other in the context of particular learning activities. Different modalities dominate communication and experiences in a classroom at different moments. Other times multiple modalities are used simultaneously; however, in some instances one modality may be more pronounced than another depending on the nature of the interactions and contexts specific to that situation. The choice of which modalities are most appropriate for the teaching and learning of subject matter at particular instances is determined and carried out by the participants (teacher and students) who are working within the affordances and constrains of that classroom.

Given that this study centers on one of my own classes, considering both my students and myself as participants in the study allows me to examine the multimodal choices students make throughout the unit in the context of the choices I, as the teacher, make in teaching within and across different modalities. Student choices may be a result of my providing them opportunities to interact within and across different modalities by prompting or requiring students to utilize various modes as part of the activity's task, or by simply allowing them access to multiple modes and encouraging them to use various modes as needed. Whether prompted or not, students use multiple modalities during group activities and experiments to express, negotiate, and construct meaning collectively. In this study, I examine how different modalities and the interplay among modalities influence and are influenced by individual and collective learning of waves and engagement in multimodal activities.

According to Kress and van Leeuwen (2001), several modes are usually enacted together that shape the multimodality of discourse. I studied modalities in my classroom as they came together to reinforce one another, but also explored modalities (e.g., hand gestures and wavy-line diagrams) that became more pronounced in the classroom discourse at various instances, and accrued meaning collectively by the students through the unit. Communication and interactions in my classroom involve various communicative modes besides oral and written language including gestures, pictures, diagrams, computer-generated graphs, data tables, numerical measurements and mathematical models, and physical artifacts. These different modalities may be present alone, together, or in place of one another. Different modalities dominated at different moments, and when viewed as a whole, multimodal discourse ebbed and flowed in my classroom. I studied this multimodal discourse to shed light on how different modalities might benefit or challenge students' conceptual development of waves and their engagement with each other in a particular context.

Conceptual development involves engagement with scientific ideas mediated by communicative acts. Halliday (1978) asserted that there are three metafunctions in any communicative act–ideational, textual, and interpersonal. Discourse participants communicate to share ideas, make meaning, and share these meanings. What ideas are developed, how they are linked to each other, and in what ways they constitute networks of meanings, all define the ideational function of communication. In this study, I explored the ideational function within various modalities and the interplay between ideas and grammatical aspects of modalities (i.e., syntactical and semantic–the semiotic system of rules, norms, organization, structures, and conventions for how meaning is constructed which define the textual function). Within each mode, ideas (*ideational* function) and grammar for engaging with a particular mode (*textual* function) are developed and shared by the participants, thus, I studied how meanings are developed and communicated among people (*interpersonal* function). I compared and contrasted how students and teacher used different modes to construct meanings within a unit on waves, using these three metafunctions as a lens, and the benefits and limitations of engagement with different modalities while engaging with each other.

Many studies utilize multimodality not as an object of study, but as a tool or methodological construct to supplement spoken and written language, such as using pictures to better access student conceptions (Smagorinsky, 2001, Tucker-Raymond, et al., 2007), or body positioning and spatial orientations to better understand discursive practices in small laboratory groups (Kelly et al., 2001), or gesturing to better capture scientific language acquisition (Roth, 2005). How might different modalities promote or limit concept development and student engagement? Who is using the different modalities, and how are they being used? What is the grammar or rules of engagement governing the use of different modalities, and how are they developed? Each communicative mode can contribute meaning to an experience or interaction, and depending on the experience or interaction, one modality may be more powerful than another in articulating an idea for a particular student within a class. Exploring multimodality for its own sake in order to understand how it shapes and is shaped by engagement with ideas, people, and contexts may be a useful addition to the literature and have implications for further research and practice. As our society marches increasingly towards multimedia, visualizations, simulations, and technology, so do our classrooms and schools. Written language is being enhanced, and in some cases replaced by other semiotic modes, and developing our understanding of the interplay of these semiotic modes in the classroom has the potential for significant benefits to teaching and learning.

II. THEORETICAL FRAMEWORK

Sociocultural Perspectives on Science Classroom Learning

Sociocultural perspectives on science classroom learning largely build on the work of Lev Vygotsky (1986), who considered the interdependence of social and cultural contexts to an individual's construction of knowledge mediated by language as a semiotic system. Espousing a sociocultural framework, I consider the science classroom learning to be a social endeavor in which teacher and students make meaning together through cultural and discursive practices. Moreover, I consider that communicative acts in a classroom are not limited to spoken or written language, but include any semiotic resources that are used for meaning making (Kress & van Leeuwen, 2001; Lemke, 1990; MODE, 2012; Roth, 2005). Thus, classroom science learning is an enculturation into the semiotic and cultural practices in which students participate as members of a classroom community (Gee, 1996; Lave & Wenger, 1991; Moje, Collazo, Carrillo, & Marx, 2001; Hicks, 1995).

From a sociocultural perspective, student participation within a community of learners dialectically shapes the meaning making process, thus making student learning highly situational. As students learn how to engage appropriately within the classroom community, they transition from legitimate peripheral participation to full participation in the community of learners (Lave & Wenger, 1991). Their participation changes from low-risk peripheral engagements common to novices or newcomers to a culture, to active and full participation as veteran members of a culture that comes with their appropriation of the culture's participation framework over time. As students appropriate discursive patterns, practices, and norms that regulate and govern their classroom's interactions, they also make meaning of ideas and concepts. Students co-construct shared knowledge and practices with their peers and teacher as they use and transform available semiotic resources as they communicate within and across modalities. During instruction, the spontaneous concepts that students develop as they experience the world in their everyday life become organized, expanded, and linked to one another as scientific concepts are explored (Vygotsky, 1986). At the same time, the scientific concepts that students study become linked to referents and gain meaning as spontaneous concepts are evoked. Vygotsky claimed that the relationship between spontaneous concepts and scientific concepts is achieved through the use of semiotic tools available to learners. Although Vygotsky focused primarily on language (spoken words and written text) as a mediating tool for concept development, non-linguistic tools, in addition to language, that teacher and students may use in a classroom are important for learning. .

Learning science involves understanding the world around us, including objects, phenomena, and processes, using semiotic resources and representations, each of which have particular meanings. Sociocultural theory posits that a science classroom community negotiates and constructs shared understandings about what is considered to be science, how science is done, who can access it, and what and how cultural tools are available and used. As students learn in a science classroom, they are socialized into a symbolic world through discursive practices in a form of a cultural apprenticeship (Driver, Asoko, Leach, Mortimer, & Scott, 1994). The semiotic resources that are used are determined by both the culture of science and the culture of schooling. Each classroom develops particular norms, values, and expectations that govern its culture and it is the science classroom culture that determines what it means to learn and do science (Lemke, 1990). Since every culture has epistemologies and ideologies that are shared among its members (Gee, 1996), learning in a science classroom involves bridging epistemologies and ideologies that students bring with them from prior experiences with those of the teacher and those of the science field (Varelas, Becker, Luster, & Wenzel, 2002). Members of a classroom community gradually converge toward a shared understanding as they interact with one another, creating a dynamic and dialogic relationship between cultural ideologies and discursive practices (Roth, 2005). Throughout this process, students' individual and collective meanings, beliefs, and practices evolve and construct the particular way of doing science in that classroom community.

Classroom science learning takes place as students and teacher communicate engaging with ideas, each other, and contexts over time. Halliday (1978) suggested three metafunctions of communication: engagement with ideas, construction of social relationships, and creation of coherence relative to the semiotic resources involved (e.g., language). These three metafunctions act simultaneously and contribute to the meaning expressed by communicative acts within a culture. Communicative acts within classroom discourse can, therefore, be viewed, and analyzed, as expressing ideas, relating participants socially, and contextualizing the norms for utilizing particular semiotic resources as part of their interactions. The ways in which these metafunctions are manifested are shaped by the communicative acts over time. Thus, developing communicative practices within a culture is a situated and highly contextualized process. A sociocultural lens on learning does not foreground the thinking of the individual as supported by social interactions and engagement with others and the environment, which is more consistent with a social constructivist perspective. Instead, a sociocultural perspective foregrounds ways in which social interactions, semiotic resources used, and one's social, physical, and cultural environment shape one's understanding or development of ideas. For example, adopting a sociocultural perspective, Roth (2005) studied how the collective language of a group converged from a brittle state to a more scientifically accurate register. Roth did not consider how an individual student's cognition drove the development of a collective language for the group, but instead considered the shared understandings of individuals that emerged within the discourse, as well as how the discourse evolved, as evidence of the group's collective understanding. As students develop discursive practices, which are influenced by their own epistemologies and ideologies, they also define what science is for their particular group (Kelly & Crawford, 1997). They develop shared scientific ideas and concepts, belief systems, language and other semiotic resources, and cultural practices that define what science is and what doing science means in their classroom.

Classroom Discourse

Classroom discourse analysis offers a glimpse into the everyday talk and interactions of students within and across activities in the classroom (Cazden, 2001). From a sociocultural perspective, teaching and learning are complex, and highly contextual and situational activities dialectically intertwined in a dynamic relationship. Discourse analysis is used to examine the canvas in which teaching and learning are socially constructed.

There is a duality involved in discourse; discourse is both a text and a socially situated, interactional process for meaning making (Hicks, 1995). Thus, discourse analysis involves attention to both the text–language or any semiotic system used to communicate ideas– and the meanings negotiated by the discourse participants. In this way, analysis of discourse allows us to investigate the construction of social meaning within culturally situated language and practices. It is important to consider how the participants in a group take on a shared language as they make meaning together. Discourses are more than dialogue, communicative acts, and interactive patterns within a community. Discourses also embody ideologies of the participants (Gee, 1996). The meanings constructed during communicative acts and interactions are dependent upon beliefs, values, norms, behaviors, actions, and feelings, which taken together define what Gee refers to as Discourse (with capital “D”). “Big D” Discourse represents a contextualized, embellished “little d” discourse, and, thus, Discourse analysis involves discourse analysis in relation to analysis of contextual elements that shape the discourse.

Furthermore, any text reflects past sociocultural contexts; that is, the utterances within a discourse are echoes of past discourses in which the speaker was previously engaged (Bakhtin, 1986). In the case of a classroom, students never come to a new class and new discourse with a clean slate; they always bring with them previous knowledge, ideologies, epistemologies, practices, and expectations based on their prior experiences. However, each classroom is a site of teaching and learning with its own culture, its own beliefs, customs, norms, habits of mind, and discursive practices. Discourse analysis can reveal a snapshot of individual and shared understandings of ideas and a culture’s different ways of engaging with ideas and one another within a particular context at the time of the interactions. It can also shed light on how ideas, as a collective effort of individuals, evolve when discourse is monitored over time. Discourse analysis offers researchers insight into what an individual student knows, what students know collectively, how meaning is negotiated and socially constructed, what cultural practices exist, and how past experiences manifest in current contexts. It allows researchers to better understand the many complexities of meaning making in the classroom.

Classroom discourse consists of the various communicative acts that are enacted during dialogue and interactions within a classroom community. Each classroom has its own semiotic systems that are shared and developed by the students and teacher as they engage with one another. Traditionally, spoken and written texts have been considered primary methods of communication among people, especially in classrooms. However, there have been calls to broaden the traditional conception of language to include any communicative act or semiotic domain (Hicks, 1995), including non-linguistic forms of interaction and communication (Wells, 2001), and multiple modes or modalities (Jaipal, 2010; Kress & van Leeuwen, 2001, Kress et al., 2006, Pozzer-Ardenghi & Roth, 2007). Non-linguistic forms of interaction include gestures, gaze, intonation, spatial orientation, diagrams, pictures, images, sketches, 3D models and artifacts, and role-playing. Broadening the definition of language and text in this way allows for consideration of any semiotic systems used by discourse participants to construct meaning together. "Meaning does not reside solely in a written text; rather, it transpires across symbolic domains" (Hicks, 1995, p. 83). Thus, considering various forms of classroom communication beyond oral and written texts enriches classroom discourse and its affordances for meaning making (Kress, 1997; Kress et al., 2006; Lemke, 1998; Prain & Waldrip, 2006). As constructs are used by the teacher and students within and across semiotic systems, shared understandings and cultural practices emerge. Classrooms develop over time their own signatures and styles for what it means to talk and do science, how negotiation of ideas and meaning making takes place, who has access to science and who does not, and how the discourse is constructed and evolves over time.

Classroom discourse is affected by the activity in which participants engage. The activity influences and limits actions, behaviors, objects, material artifacts, and spatial orientations with which students make meaning both individually and collectively (Roth, 2005). As classroom participants interact in the context of an activity, meaning is developed and communicated. Language (considered here in its broad sense to include linguistic and non-linguistic aspects) utilized in these social interactions should not be merely thought of as a tool for the expression of ideas. There is a dialectical relationship between meanings and means for communication of these meanings. In a science classroom, as students' scientific language develops, students do not merely develop a better means for expressing their understanding. Instead, as their language grows, so does their understanding, and as their understanding grows so does the language they can use to articulate it. This is one of the essential elements of Vygotsky's (1986) theory, linking the development of thought and language (or thinking and speech). As we express our ideas through language and other semiotic systems, the ideas are fleshed out, articulated, organized, modified, clarified, and corrected, which leads to further development of language. This process shapes the ideas being expressed and developed. Understanding what semiotic systems are called upon during meaning-making, how and under what circumstances they are enacted, and why a particular system is utilized over another may offer insights into the potential benefits and limitations of various semiotic systems to students' learning of science.

In a science classroom, language development and concept development are mutually constitutive. As students' understanding of scientific ideas improves, so does their ability to accurately talk about those ideas (Lemke, 1990; Roth, 2005). However, developing students' language and developing students' understandings in the science classroom are quite complex processes. Roth (2005) contended that during convergence towards a stabilized language, students' talk would appear to align with accurate scientific language, but "should not be overinterpreted, as the language is still brittle and needs to accrue to their already existing familiar world" (p. 78-79). Thus, students' brittle language should be gradually fostered and stabilized through participation in classroom discourse–using and interpreting language, and receiving feedback from teacher and peers. Stabilization and understanding are reached as students engage in discourse over various lessons and communicative modes, leading to alignment with a canonical scientific view (Roth, 2005; Prain & Waldrip, 2006). This perspective on scientific language convergence and stabilization exemplifies the complex nature of classroom communication and interactions.

Classroom discourse is also affected by the activity structure. Doing an experiment, listening to a lecture, discussing homework are all examples of activity structures, each with its own discourse genre. Research into classroom discourse has revealed different genres that can be readily observed, such as the traditional IRE/IRF (Sinclair & Coulthard, 1975; Mehan, 1979), triadic dialogue (Lemke, 1990), narrative discourse (Hicks, 1995), and nontraditional heterogeneous or hybrid discourse practices (Kamberelis, 2001). Examining discourse genres can provide a variety of insights into issues, such as what conducting an experiment looks and sounds like for a particular group in this classroom, and what procedures, interactions, or organization frameworks are expected and enacted by participants in a particular genre. Activity structures and discourse genres are intimately connected (Hicks, 1995). In fact, for Lemke (1990) they are identical.

According to Lemke (1990) discourse genres, or activity structures, are organizational patterns of interactions and goings-on of a lesson. For example, the traditional IRE/F (Initiation-Response-Evaluation/Follow-up) genre of classroom discourse is often the customary activity structure of teacher-led instruction. The teacher asks the class a question, a student responds, and the teacher either publically evaluates or follows up with another question. Discourse genres may serve several functions for the teacher (Wells, 1993; Lemke 1990). Lemke (1990) discussed the dual function of triadic dialogue (or IRE) to both teach content and maintain control. The teacher is the authority controlling what questions are asked and who will speak, and evaluating whether a student’s response is correct or not. In this regard, the teacher is both a knowledgeable authority of content, and in authority of classroom procedures, structures, and activities (Oyler, 1996). However, a teacher may intend to enact an IRE discourse, but allow an alternative genre to emerge spontaneously. For instance, a student raising his or her hand as a bid to challenge the teacher's point of view might not align with the teacher's intended sequence, and forces the teacher to either dispel it and go back to the intended structure or to proceed into a different discourse genre where the student and teacher now share authority (Lemke, 1990; Oyler, 1996), which Oyler refers to as a *breech*. Such alternate or competing genres may create tensions within a classroom community. The lack of shared understanding of how to participate, interact, and communicate might be confusing. However, such tensions can be avoided by structuring activities to allow for such competing genres to emerge as expected and intentional forms of participation. Allowing and encouraging students to ask questions or argue amongst themselves may create interactional spaces for students to engage in science or any other subject matter. Spontaneous breeches in discourse can provide powerful learning opportunities, but also risk loss of coherent structure in addition to loss of teacher control of the discourse, which may or may not be a desirable outcome (Kamberelis, 2001; Oyler, 1996).

Kamberelis (2001) refers to discourses that consist of such jumps to alternative genres as *hybrid* discourses, which he described as emergent and self-organizing. The teacher can intentionally and strategically create these spaces for students, but they are ultimately "contingent [upon the] actions and reactions by the individuals, social, and material agents and agencies" (p. 89). These emergent discourse genres can co-exist with other genres in the same activity. Kamberelis also claimed that hybrid discourse practices afford opportunities for students to take ownership of the discourse at times, thereby allowing for their own thinking and conceptions to weave into the classroom discourse. In addition to providing students with spaces in the discourse over which they have ownership, hybrid discourses can also offer the teacher insight into what students understand and how they construct meaning (Oyler, 1996).

In classroom discourse, participant interactions depend on the social interfaces present in an activity. Considering that a classroom consists of students and a teacher, together making up the classroom community, four social interfaces may be present in an activity: student-student, student-community, student-teacher, and teacher-community. In student-student interfaces, students in either small groups or during whole-class discussion interact without a teacher being a discourse participant. In student- community interfaces, a student interacts with the entire classroom community including teacher and peers. In student-teacher interfaces, a student and the teacher engage in a dialogue, such as when a student asks the teacher a question or vice versa. In teacher-community interfaces, the teacher communicates with the entire classroom community at once, such as in a lecture. Different discourse genres may be enacted in the same interface depending on the power hierarchy or social roles of the participants, which may be based on participants' perceptions of themselves and each other. For instance, if a group of three students were to interact while conducting an experiment, and one of the students was considered by the group to be an authority on the content, a traditional IRE genre might emerge, with its own local framework for participation, as the authoritative student attempts to explain his or her point of view to the rest of the members. This can be contrasted with the same activity structure and the same social interface, but where all participants viewed each other as equal authorities over content and procedures. In this case, a discourse genre that favors shared authority might emerge with its own framework for participation. Therefore, discourse genres can be contingent upon social interfaces within an activity. They may also be purposefully selected by the teacher or emerge discursively as breeches that lead to hybridity in the discourse as noted previously.

Studies of classroom discourse explore the detailed interactions within a classroom and the moment-to-moment events and actions that constitute students' engagement with ideas, one another, and the environment. The merit of classroom discourse analysis is recognized in both psychological (e.g., sociocognitive or social constructivist) and sociocultural research paradigms, albeit with different approaches and research foci. In my study, I use discourse analysis to capture and explore the social interactions and engagement of my students with ideas, each other, and their environment as they learn about the physics of waves.

Multimodality

There is much more to human interaction than linguistic exchanges among people. Thus, teaching and learning involves both linguistic and non-linguistic modes of communication. Face-to-face communication is only partly verbal; meaning is shared and created via a myriad of non-linguistic cues that occur along with, or separately from, linguistic exchanges. In fact, one can say a lot without any words at all. Roth (2005) points out the example of a passenger on a plane who communicates his desire for a cup of coffee by the mere nodding of his head. In our day-to-day interactions, countless examples of non-linguistic communication are realized. In some ways, non-linguistic communication, such as images, can be even more powerful than language, as seen with many everyday advertisements (Kress, 2006). The plurality of communicative modes, or semiotic domains, across which meaning may be constructed and shared is captured in the construct of *multimodality* (Kress & van Leeuwen, 2001). In educational studies of classroom discourse, exploring multimodality involves analyzing the linguistic alongside other communicative acts, such as gestures, diagrams, images and pictures, materials and artifacts, gaze and facial expressions, and body positioning and spatial orientations (Jaipal, 2010; Kress et al., 2006; Prain & Waldrip, 2006). Multimodal discourse consists of various different modalities that are used together or separately over a period of time during which participants make meaning. Analyzing multiple modalities can allow researchers to develop a more thorough and rich description and understanding of classroom interactions. Multimodal discourse analysis parallels in some ways a traditional discourse analysis of speech acts in a dialogue (Gumperz, 1982), but is much broader in scope to include other modes used for communicating and constructing meaning within a setting.

How a concept is learned depends on the modality in which it is represented (Kress et al., 2001). Meanings constructed depend on the semiotic resources used, which include actions, materials, and artifacts people use to communicate (van Leeuwen, 2005). Semiotic resources, which are socially shaped within a culture and organized in particular ways, define the characteristics of a mode (Kress, 2009). According to Halliday (1978), any form of communication and, thus, a mode, need to satisfy three metafunctions—ideational (description of ideas), interpersonal (shaping of social context), and textual (organization of semiotic resources). Examples of modes include images, diagrams, writings, layouts, speech, music, gestures, and videos or moving images. In general, different modes may represent similar ideas, but each captures ideas in different ways that, whether beneficial or limiting, contribute to the overall meaning constructed.

In a science classroom, the choice and use of particular modes impact how students appropriate concepts and relationships among concepts. Students' ability to utilize a particular mode accurately and engage with an idea across modes represents what Pierce (1931-1958) called *representational competence*. Students' understanding is contingent upon their ability to navigate among various representations. Important questions that need to guide our understanding of the role of multimodality in teaching and learning within a classroom include:

How do students socially construct their representational competence as driven by the social interactions and engagement within a particular context? When do students and/or teacher choose to draw a picture or diagram to aid their speech in describing an idea? How prominent are gestures during classroom discourse and how are gestures used by speakers? In what instances do students and/or teacher elect to shift to a mode other than speech, and how does this help them to articulate their idea?

One mode is not necessarily always better than the rest for developing and sharing ideas, albeit the fact that spoken and written language is traditionally considered as primary (Cazden, 2001; Kress & van Leeuwen, 2006; Lemke, 1990). Various modes may be used alone, or together with others to reinforce one another and enable discourse participants to clarify, articulate, extend, construct, and communicate meaning (Jewitt, in Kress & Mavers, 2009; Lemke, 1998). Lemke refers to scientific concepts as *semiotic hybrids* because their meanings derive from the interaction among multiple, simultaneously occurring, semiotic modes. Each mode affords, that is, carries, enables, and supports, a different meaning potential, and these meaning potentials can be combined and fused into one when the modalities are utilized simultaneously or in conjunction with one another. For example, a picture alone can be interpreted in a variety of ways, but when it is presented alongside verbal commentary and gesturing, its meaning becomes interwoven with the meanings communicated by the other modes. In other words, each mode has particular affordances for meaning making, or meaning potentials (Kress & van Leeuewen, 1996, 2006). When multiple modes are present, the overall meaning is created collectively from all of the modes' meaning potentials, each contributing or reinforcing different aspects to the process as a whole (Lemke, 1998). Thus, although each mode in multimodal discourse has its own potential strengths and limitations, when multiple modalities come together, a more enriched understanding of concepts may be achieved.

When students have not developed fluency in a particular mode, shifting engagement to other modes may be especially important. For example, young children lack a fully developed language, which is similar to high school physics students who lack a fully developed *scientific* language for communicating about phenomena, which limits the students' ability to engage in scientific discourse. Although many physics students in secondary classrooms can read, write, and talk well, they usually have limited fluency in reading, writing, and talking *science* (Roth, 2005). For example, Roth found that deictic and iconic gestures often precede the corresponding words or verbal language for students referencing different entities. As a result, gesturing plays a critical scaffolding role in the development of scientific language and discourse. As this example shows, combining linguistic with non-linguistic modes in science classes is particularly important.

As students develop conceptual understandings, they also develop skills for articulating and communicating their ideas within and across different modes. Learning science implies that students are able to translate between and across multiple modes (Lemke, 1998; Prain & Waldrip, 2006). Those with a fully developed conceptual understanding should be able to recognize the different strengths and weaknesses that each mode has in representing a scientific concept in order to flexibly move between and among modes, as well as to elect the most appropriate mode for a particular context or concept. A more articulate understanding of concepts is accompanied with a more articulate aptitude with *multiple representations* of these concepts (Ainsworth, 1999, 2006; Ainsworth & Loizou, 2003; Oh & Oh, 2011; Prain & Waldrip, 2006). Thus, to support learning, teachers should offer students opportunities for, and guide them toward, using *and* constructing multiple representations (Prain & Tytler, 2012).

Different modes offer different opportunities for communicating an idea and constructing meaning related to this idea. These opportunities are shaped by individuals' ideas, sociocultural elements (such as context and social interactions within this context), and modal affordances. Moreover, one's ideas not only shape the engagement within a particular mode or modes, but are also shaped by the engagement. The ways in which students communicate their ideas using a mode or modes can both indicate their current knowledge, as well as illuminate the learning that takes place as they engage with that mode or across various modes. Engaging with a mode, or modes, affords new meaning that influences and shapes students' ideas, and is thus not only capturing a pre-existing idea. For example, Smagorinsky (2001) found that the act of drawing led to more articulated meanings for the student authoring the illustration. As one student said, "at the end, I understood what I was doing more than I did when I began the drawing" (p. 147). Although this comment alone is not evidence of learning, it suggests that for that student, drawing was not merely a means of revealing conceptions, but was instead a *process* of learning. The meaning potential of drawing complemented that of the written text, and the act of drawing afforded different layers of meaning related to the ideas about which the student was writing. Learning can be thought of as the development of semiotic resources, that constitute particular modalities, upon which students can call to make meaning (Roth, 2005). Meaning and semiotic resources for articulating it are dialectically constituted, and develop in tandem.

As people develop a language, or any semiotic system for representing aspects of reality, they are developing higher mental processes (Vygotsky, 1986). Thus, conceptual understanding coevolves with the development and use of language for communicating concepts. Expanding the traditional notion of language (i.e., written and spoken linguistic systems) to include other communicative modes, such as gesturing, sketching and drawing, and manipulation and use of artifacts, is especially critical in contexts where students lack a shared linguistic system (Jaipal, 2010; Kress et al. 2001). In his work *Talking Science* (2005), Roth used multimodal elements of classroom discourse, such as gesturing and use of artifacts, to gain a better understanding of how learning scientific language coevolves with learning concepts. His focus was on the relationship between verbal language development and conceptual development for groups of students interacting with one another and the teacher. Roth asserted that while students attempt to orient themselves within an unfamiliar environment, they do not have a shared, stabilized, and accurate language for guiding each other through the activity. In such cases, gestures, for example, provide important resources by aligning participants to something one has identified, even if a descriptive language does not yet exist for the students (Roth, 2005). On their own, gestures may not carry much meaning, but when used in conjunction with other modes, such as diagrams and verbal utterances, students can articulate ideas and meanings across other modes, mediated by gestures, which might not be possible if a mode is acting alone.

Each communicative mode has its own syntactic and semantic rules and patterns (Lemke, 1990), or visual grammar (Kress & van Leeuwen, 2006). Syntactic rules specify the ways in which features of a mode are used together within a communicative act. Semantics capture the meaning or interpretations of the representations used within a mode. For example, using one's hand to point at a door is a syntactical rule for calling attention to a door. The meaning or interpretation of this communicative act as a command telling someone where to go constitutes its semantics. Similarly, in the diagrammatical modality, instead of a hand gesture pointing to a door, a sign with an arrow points at a door. The two examples carry the same deictic function and semantic pattern, albeit via different modalities each with its own syntax. The syntax and semantics make up the grammar for a particular mode, which is developed and put into practice by participants over time.

It is also critical to recognize that the grammar (i.e., syntax and semantics) of any mode is not static or fixed, but is shaped through its cultural, historical, and social uses (Jewitt, 2009). The use of any mode is highly contextualized and situated in the moment that a person calls upon that mode to communicate. A mode is used according to the grammar understood by that person as based on its historical and cultural usage, but can also be influenced and shaped by the person's motivations and context at that particular moment. Social adaptations and interactions can shape how a mode is used, and thus, its grammar can change over time (van Leeuwen, 2005). Regarding teaching and learning, both syntax and semantics (i.e., grammar) are developed and articulated by students and teacher over time throughout lessons and activities in a classroom. Students and teacher develop how various modes, and the features or semiotic resources of a particular mode, can be utilized to convey meaning and communicate ideas. The syntactic and semantic features of the modes employed influence one another shaping the multimodal classroom discourse and ultimately students' learning and engagement.

The availability and use of particular modalities in a classroom are often controlled by the teacher. For example, in a teacher-led lesson, the teacher may choose to use certain modalities, such as speech and diagrams, to more clearly and efficiently express a concept, or to model how a particular modality (e.g., a diagram) should be used by the students in the future. Kress et al. (2001) described a teacher-led lecture in which the teacher selected to elaborate on meanings through linking a diagram of blood circulation with the teacher's speech and gestures about it. The affordances of each modality strengthen the meaning that the teacher attempts to communicate to students. In student-centered activities, the teacher may provide opportunities for students to communicate within and across different modalities in order to develop students' syntactical and semantic skills for utilizing and constructing modes to make and negotiate meaning.

Many studies examining multimodality in science classrooms in particular focus on the teacher's use of modalities during lectures (Jaipal, 2010; Márquez, Mercè, & Espinet, 2006; Pozzner & Roth, 2006). For example, in an attempt to better understand how teachers used various modes in lectures, Márquez et al. (2006) investigated the different modalities of instruction used by teachers while teaching the water cycle to create an analytical scheme for discourse analysis. A far smaller number of studies have examined how students use multimodality to construct understandings and learn science (Jewitt et al., 2001; Kress et al., 2001). To develop a more complete picture of teaching and learning in a science classroom, exploration of both teacher's and students' use of multimodality during the meaning-making process is necessary. Kress et al.'s (2001) work was among some of the first comprehensive multimodal research on teaching and learning in the science classroom. In their book, the authors described not only the teacher's use of multimodality during lectures, but also investigated students' learning as a "dynamic process of transformative sign-making which involves [social interactions of] both the teacher and students" (p.10), taking a multimodal social semiotic approach to analyzing the students' interactions within the classroom's multimodal discourse. They examined the texts and semiotic resources called upon and used by the students, and considered the differences between texts (and semiotics resources) produced by the teacher and students, respectively. The authors call for the need for science education researchers, and those focusing on multimodality in particular, to consider students' multimodal discourse as a framework for investigating student learning, in addition to teaching, in science classrooms. My study examines both the teacher's and students' use of various modalities, and the co-construction of students' conceptual understanding and multimodal discourse in which they are engaged.

As noted previously in the section on Classroom Discourse, Gee's (1996) Big "D" Discourse captures the ways of knowing and doing in a social context. Although his construct of "Discourse" expanded the notion of "discourse" to consider contextual elements and social practices of a discourse community, it did not explicitly attend to multimodality. The focus of Gee's framework is the embedded ideologies of a community without explicitly considering the particular features of various modalities within a discourse and their contributions to the meaning-making process of the discourse participants. Although Gee does not explicitly relate his framework to multimodality, the ways of interacting that Gee discusses extend into non-linguistic dimensions of discourse such as gesture, gaze, proximity, and tone, which constitute semiotic resources of various modes. Tucker-Raymond, Varelas, Pappas, and Wentland (2007) investigated the ideologies behind children's conceptions of who scientists are and what they do, which the authors monitored over time. Tucker-Raymond and his colleagues used multiple modalities, namely speech and images (i.e., children's drawings), to develop more comprehensive narratives that offered insights into children's conceptions about science and their place in science. Both Gee's Discourse framework and a multimodality framework consider communicative acts within classroom discourse to be highly situated and driven by cultural, contextual, and social aspects. In addition, the ways in which a particular group of people interacts within a culture are transformed as time goes on, reshaping a mode's grammar, its semiotic resources, and usage.

In the same way traditional language shapes what counts as science (Lemke 1990; Roth 2005), multimodality shapes what counts as science, and what it means to engage in scientific practices. Multiple modalities mediate and constitute classroom Discourse (with a Big “D”) that coevolves with students’ learning of science as a social practice. When students are given access to, and engage in interpreting or constructing meanings in, different modalities, their interactions are mediated by a richer semiotic canvas that facilitates their collective meaning making. This canvas not only combines and multiplies meaning potentials, but is also transformed over time by the participants’ discursive practices. Students have much more communicative flexibility if they are provided with opportunities to utilize multiple modes of communication to better express, clarify, and articulate their thoughts during their interactions (Roth, 2005). This may in turn enrich students’ conceptual development by providing alternative semiotic systems with which they can reason and communicate with one another as they make and negotiate meaning.

In classrooms, multimodality may be planned or may spontaneously emerge, without being part of the teacher’s intended activity structure, as a response to various communicative acts taking place in the classroom. An example of planned use may include a teacher’s inclusion of diagramming in a lecture or a teacher’s prompting students to draw a diagram. Unplanned, or emergent, multimodality may spontaneously bubble up in the discourse when students are given a share of the authority over the discourse practices. For instance, when a student in a physics class poses a question to the teacher asking to articulate a homework problem’s context, the teacher might respond by gesturing, drawing a diagram, or role-playing the situation to better explain the context of the problem that the student is struggling to understand from the written and verbal explanation alone. Thus, there may be a shift (or what Kress (1997) called *transduction*), from one particular mode or modes to another. In this example, the multimodality in the teacher's response is emergent. Students may also call upon an alternative modality during interactions within a small group as they negotiate meaning together. For example, as a student in a small team of three students suggests an idea related to how to move an artifact during an experiment, he or she might enact the suggested movement using a gesture. The gestural mode emerged as the student selected it to add more meaning to the communicative act that speech alone could not achieve. Which mode or modes emerge may depend on what modes are socially available at a particular moment, the amount of time allowed for a communicative act, the participant's epistemic understanding of a particular mode with regards to recognizing when it is appropriate to select it and how to successfully engage in it, and even the nature of the idea. Another example of when modalities emerge includes a teacher prompting students to further articulate their spoken ideas. A student may elect or be prompted to draw on the board or deictically gesture to an artifact to add more meaning to speech. These transductions between modalities are highly contextualized and situated in the moment and within a particular discourse. In regards to discourse genres as discussed earlier, emergent multimodality can be thought of as breeches in the multimodal discourse. As previously discussed, these breeches create spaces where students share authority with the teacher and may provide students with meaningful opportunities for student leaning. Emergent multimodality has not yet been studied in multimodality literature, but it is a fruitful research opportunity. Examining how modalities emerge provides insights into understanding the ebb and flow of multimodality in a classroom.

In this study, I will use Halliday's (1978) work, which I referenced earlier, in order to study the communicative functions of both linguistic and non-linguistic modalities, reflecting a broader view of language. Halliday asserted that there are three metafunctions in any communicative act–ideational, textual, and interpersonal. Discourse participants communicate to share ideas, make meaning, and share these meanings. What ideas are developed, how they are linked to each other, and in what ways they constitute networks of meanings, all define the ideational function of a communicative act. Communicative acts constructing and enacting social interactions between people as they engage with ideas function to socially position the participants with one another, and the meaning that is made via social exchanges between individuals. Students' social relationships with one another both affect and are affected by their interactions. The norms and means by which a modality can be enacted to generate meaning is the textual function. The textual function depends on the grammar of a particular mode, which is negotiated by the participants as they interact over time.

Regarding the many modalities in a science classroom, diagrams and gestures are generally typical modalities used by teachers and students and are, therefore, of particular significance to examine when studying multimodality in a science classroom (Jaipal, 2010; Kress et al. 2001; Márquez, et al, 2006; Roth, 2005; Pozzer-Ardenghi & Roth, 2010). Gesture is a modality that often adds meaning when accompanying other modes such as speech (Goodwin, 1981, 2000; McNeill, 1992, 2000; Roth 2005) and visual modalities (Pozzer-Ardenghi & Roth, 2007, 2010; Roth 2001). Most gestures in science classrooms function to point (deictic gesture) or to represent in form or resemblance (iconic gesture) (Kress et al., 2001; Pozzer-Ardenghi & Roth, 2007; Roth, 2001, 2010). Deictic gestures call the collective attention of a group to certain visual features, characteristics or aspects of another modality, such as written text, mathematical expressions, pictures, diagrams, graphs, and objects and artifacts, by pointing. Pozzer-Ardenghi & Roth (2010) describe how a teacher's speech referring to an aerial photograph can gain additional meaning when combined with deictic gestures highlighting an area or pointing to a particular location in the photograph. Iconic gestures function as imagistic representations

(McNeill, 2000) by depicting an aspect or characteristic of a visual entity through resembling its concrete visual characteristics. These gestures embody aspects of the image or artifact they aim to represent, and can help call attention to or enact these characteristics in a dynamic way. Because one's hand can move, static visual elements from a picture, for instance, that are embodied by one's hand can also be set into motion by an iconic gesture that enacts the motion. Regarding iconic gestures, McNeill (1992) suggested that hand gestures may also impact thought, acting as symbols or semiotic resources that exhibit meaning in their own right even if accompanying speech or other modalities. In considering gestures as an integral part of the communicative and meaning-making process, as opposed to a supplementary mode that is subordinate to linguistic modes, affords another tool for understanding meaning-making processes, including teaching and learning science.

Gesturing in science education is a relatively new area of research led largely by the work of Roth and his colleagues over the past decade. Much of the research into gesturing in science classrooms focuses on either the gesturing of the teacher (e.g., Hwang & Roth, 2011; Pozzner-Ardenghi & Roth, 2010; Roth & Lawless, 2002b) or students (Givry & Roth, 2006; Roth & Lawless, 2002a; Roth & Welzel, 2001). The issue of how gestures might transform and take on meaning as both teacher and students use them over time has remained unexplored. For example, studies of teacher use of gestures during lectures and instructional practices have found that bodily movements co-articulate concepts in real-time in the presence of an audience (Hwang & Roth, 2011). The teacher's simultaneous gestures and other communicative acts blend together to construct the scientific concepts being presented, a process referred to as *lamination* by Roth and Lawless (2002). Studies of how students use gestures in science classrooms have found that students' understanding of concepts or *conceptions* include all semiotic resources since talk and gesture act simultaneously, and iconic gesturing requires students to identify relevant structures in the setting to enact as meaning-making resources (Givry & Roth, 2006). A focus on gestures have also been used to understand how students make meaning of photographs in a biology classroom (Pozzer-Ardenghi & Roth, 2003, 2004), and how students use gestures with speech as they encounter unfamiliar laboratory environments in a physics classroom (Roth & Lawless, 2002a). Gesturing is also shown to play a key role in students' scientific language development (Roth & Lawless, 2002a; Roth, 2005). However, a research focus on the relationship between how a teacher uses or models gesturing to communicate scientific ideas *and* how students may take on such actions in their communication of scientific ideas over time may offer insights into science teaching and learning that focusing only the teacher or the students may not. As students and teacher gesture, the cultural and situated meaning for when and how to gesture is negotiated discursively, in addition to the scientific concepts the gestures mutually constitute with other modalities. As with the case of gestures that emerge from laboratory activities in which students manipulate artifacts, these iconic gestures take on situated meanings that are later called upon when students describe and explain their actions and observations from the laboratory experience (Roth & Wetzel, 2001). Such meanings, captured, enacted, and developed over time via iconic gestures, reflect cultural elements that are developed socially, constructed by both teacher and students over a period of time and lessons, and, thus, reflect an untapped, yet potentially fruitful, area for research in science education.

Visual depictions or reproductions of an entity that retain some of the entity's features or likeness are generally referred to as images (Kress & van Leeuwen, 2006), or inscriptions (Roth, 2005). Visual depictions include photographs, diagrams, drawings, graphs, film, paintings, sculptures, advertisements, and models. They can even take the form of more abstract entities such as memories and mental models created from verbal descriptions. Images carry different meaning potentials that are not only based on an image's characteristics, but also on readers' visual grammar upon which they form interpretations and meanings of the image (Kress & van Leeuwen, 2006). Although images can include a wide variety of visual representations, diagrams are especially relevant to the teaching and learning of science and abundant in science classrooms.

Diagrams provide a referent with which teacher and students can engage, and contain a system of non-verbal semiotic resources that articulate ideas when talk alone may be insufficient or difficult. The production of diagrams, and their utilization as semiotic resources, is a process developed over time and interwoven with student learning. For instance, in diagramming an observed event or another image such as a photograph, one is forced to abbreviate the many characteristics of a photograph and only draw certain features, which are selected based on thinking at that particular moment and context. The semiotic resources called upon in generating a diagram have situated meanings that are shaped over time as they are utilized by participants across contexts. As the teacher and students produce diagrams together, the grammar of how diagrams are drawn in particular contexts and how they express scientific ideas and concepts is also shaped over time. Participants use both spontaneous methods for diagramming as motivated by the needs of a particular context, as well as learned understanding related to diagramming syntax. As students use diagrams as a mode of communication of their ideas with one another, individual and collective diagramming practices and semiotic resources, as a cultural element of the class, are also being negotiated, and thus shaped by participants over time. Teacher modeling of diagramming practices may further promote students' enactment of particular diagramming practices as students could call upon these semiotic resources during future diagramming opportunities.

Diagramming, as a mode frequently used by teachers and students in science classrooms, often takes the form of free-hand drawings produced by teacher and students or existing diagrams created by some other author such as the author(s) of textbooks and electronic media. Diagrams are visual depictions of some reality which the author represents in an abbreviated and often contrived way through the production and use of signs (Kress & van Leeuwen, 2006). The abbreviations are often used to foreground particular aspects while minimizing or omitting those aspects the author has deemed superfluous. Contrived elements that do not physically exist can be added such as arrows, captions, and labels, all of which provide interpretive suggestions to the reader of the diagram. For these reasons, diagrams are a powerful modality of communication and meaning-making and are abundant in the discourse of science classrooms.

The ways in which diagrams have been involved in science education research varies. A source of variation is related to the sign-maker or author of a particular image. Studies have focused on a teacher's production of diagrams during instruction, which shapes the classroom's scientific discourse and impacts students' learning (Jewitt, Kress, Ogborn, &Tsatsarelis, 2001; Marquez, Izquierdo, & Espinet, 2006; Prain & Waldrip, 2006; Roth 2005). In such studies, a teacher's lecture or talk was found to be a blend of simultaneous linguistic and non-linguistic modes that multiply the meaning co-constructed between teacher and students. Studies have also focused on students' interpretations and use of diagrams provided by the teacher or textbook. In these cases, researchers examined the meaning-making and discourse related to the diagram as teacher and students try to take ownership of the diagram by interpreting and discussing its features (Ainsworth & Th Loizou, 2003; Jaipal, 2010; Roth, 2005). Consideration of both teachers' and students' production and use of diagrams in science classrooms offers a unique research perspective that examines bridges between how teacher and students produce diagrams, and the dialogical relationships that enable it (Jewitt, Kress, Ogborn, Tsatsarelis, 2001; Prain & Waldrip, 2006). Moreover, studies have focused on diagrams that students themselves produce in science classrooms (Cook, 2006; Gobert & Clement, 1999; Jewitt, Kress, Ogborn, &Tsatsarelis, 2001; Pappas, Varelas, Ciesla, & Tucker-Raymond, 2009; Prain & Waldrip, 2006; Tucker-Raymond, Varelas, Pappas, & Keblawe-Shamah, 2012; Varelas, Pappas, Kokkino, & Ortiz, 2008; Varelas & Pappas, 2013; Varelas, et al., 2007; Waldrip & Prain, 2010). Student-created diagrams have been found to be windows into students' thinking and conceptual understanding, and into their past experiences that had influenced the ideas they depicted.

As students learn scientific concepts and ideas, they are better able to express concepts and ideas across multiple representations, including but not limited to diagrams (Ainsworth, 1999, 2006; di Sessa, 2004; Prain & Waldrip, 2006). Students make choices as they draw diagrams, which represent what they see or envisage regarding a topic, which provides evidence for their understandings. However, multiple modalities, of which diagrams may be one, also facilitate students' construction of ideas that are shaped and developed as teacher and students engage in multiple modalities (Jewitt, Kress, Ogborn, Tsatsarelis, 2001; Lemke, 1998). What is also important to consider is that in classroom discourse various modes are interwoven and linked to one another representing ideas. For example, as a student uses a diagram to explain an idea to his or her peers, the diagram itself does not carry the full meaning potential during the interaction, since other modes, such as talk and gestures, may be inextricably woven creating the fabric of multimodal classroom discourse. It is the dialogical relationship among modes (linguistic and non-linguistic) that form the canvas for meaning-making in science classrooms.

Diagrams are, therefore, a part of a larger multimodal landscape that shapes each modality called upon and utilized by classroom participants. For example, in the study conducted by Marquez, Izquierdo, and Espinet (2006) in the context of a unit on the water cycle, diagrams were pronounced in the classroom multimodal discourse, but the talk and gesturing about the diagrams was necessary for the researchers to analyze in order to understand how diagramming aided the teacher's instruction. There is, however, a dearth of research exploring both teacher and student use and creation of diagrams and their evolution over time along with their relationship with other modes in terms of meaning making.

Waves

Research on how students learn about waves is limited and largely dominated by studies focused on student conceptions and mental models, and used constructivist-based frameworks (Fazio, Guastella, Sperandeo-Mineo, & Tarantino, 2008; Hubber, 2006; Wittmann, 2002). Mechanical waves may be generally associated with two essential models each of which allows different aspects of waves to be more or less pronounced. One model represents the motion of a wave's pulse, or propagation, which Wittmann (2002) calls the *pulse model*. The pulse model considers the wave's disturbance or vibration (pulse) as an object moving with, or being transmitted by, the wave. It is relevant to consider the pulse when exploring answers to questions, such as: what is the speed of a wave, and how long or how tall is the wave? Considering waves from the pulse model perspective may be especially useful to teachers and students beginning a curricular unit on mechanical waves (Fazio et al., 2008). The pulse model considers the wave to be a fixed entity moving at a constant speed, which reflects a basic and fundamental type of motion (constant speed) with which students are often already familiar.

The pulse model represents what Fazio et al. refer to as macro-level motion, which emphasizes aspects of the wave pulse's propagation and characteristics, all of which are easier for students to observe and visualize. For instance, students can see a pulse move down a long slinky, or watch a human wave move through a crowd at a large sporting event. The macro-level features of a wave can be captured and explored within and across multiple modalities; students can be part of the human wave or they can generate the pulse on a long slinky, and they can talk, write, gesture, draw, diagram, manipulate artifacts, and act to communicate and develop meanings. In my study, I focus on macro-level aspects of a wave pulse propagating down the length of a slinky during initial inquiry-based investigations in which students examine particular wave characteristics, such as propagational speed, amplitude, and frequency (period, or pulse width if using a single pulse).

As students begin to develop macro-level scientific concepts, they can transition toward engaging with the other wave model–the *micro-level* model, which represents the oscillatory motion of a medium's particles. This model is also referred to as either the *entity* model (Linder, 1992) or the *particle* model (Wittmann, 2002). In contrast to the macro-level model that describes a wave's propagation, the particle model is a micro-level model that describes motion in ways much less salient to the student's everyday experiences and observations. This model of wave behavior is, therefore, more challenging for students to appropriate. Transverse and longitudinal waves are examples of a classification based upon the particle motion of a particular wave, demonstrating that not all waves' particles move in the same way.

Investigations of the particle motion of waves can be coupled with oscillatory motion to bring micro-level aspects to a macro-level experience in which students can more meaningfully engage. Such investigations include measuring the physical movement of an oscillating mass attached to a spring (Kelly et al., 2001). Kelly and his colleagues pointed out the benefit of such a setup in that “the real-time presentation of data displays afforded the students the flexibility to explore ideas, formulate conjectures, test initial hypotheses, and examine multiple interpretations of physical events” (p. 140). Given the difficulties in investigating micro-level phenomena, the macro-model of the pulse might provide students the necessary scaffolding as they first explore wave characteristics.

Waves are a fundamental topic to any secondary physics classroom and teaching about waves, as many other physics topics, can be rich in opportunities to engage with various modalities. Both the easily observable and more abstract aspects of waves can be used to support students’ meaning making. Students can create a wave on a long metal slinky through the movement of their hand, but they can also experience the energy carried by a wave by associating it with the disturbance or vibration they feel as a wave hits their hand or moves the slinky as it passes through. As students engage in such activities, they have opportunities to use various modalities in addition to oral and written language, such as gestures (including hand waving back-and-forth), wave diagrams, sinusoidal waveform graphs, and use and manipulation of artifacts such as a long metal slinky.

III. METHOD

This teacher research project explored the nature of multimodality in my classroom in the context of an instructional unit on waves, and the affordances, limitations, and challenges multimodality offered students with regards to their conceptual development and engagement. As a teacher researcher, I chose specific content or concepts for my students to learn, as well as the lesson structures and contexts in which my students engaged. My pedagogical choices shaped the activity structures I instituted, and, therefore, influenced students' interactions and experiences that took place within them. In this study, I was both the teacher and active participant in the community and multimodal Discourse that I was studying, and the researcher who analyzed this multimodal Discourse. As a result, my teaching choices and pedagogical acts influenced my research, and my research intentions influenced my pedagogy.

My tensions as a teacher researcher involved my ability to synthesize these two roles of being a researcher interested in understanding, and a teacher interested in helping students learn (Wong, 1995). For instance, I had to find a balance between being a teacher who wants to scaffold and a researcher who wants to listen. To alleviate these tensions, I wove together my interests as a teacher and researcher into one overall goal–to help my students learn by listening and guiding (Wilson, 1995). According to Wilson, engaging in teacher research is all about striking a balance. On the one hand, I need to lead, control pace and efficiency, tell and explain, intervene and scaffold; and on the other hand, I need to allow students to work together through a problem, make their own choices, and expand and articulate their own ideas all while I listen. Both sets of practices are necessary for student learning when used appropriately. Thus, in this way, there is little tension between being a teacher and a researcher. My study examined the moment-to-moment events and interactions that occur within this balance.

In order to study how multimodality shapes and is shaped by student learning and engagement, I had to be mindful of what I am doing as a teacher to promote use of different modalities through my pedagogical choices. For example, how do I model the use of various modalities? In what modalities are my interventions and scaffolds? How do my tasks and activity structures suggest, promote, or challenge students' multimodal discourse? To what extent do I provide my students access to multiple modes as they make meaning with one another?

Participants

Since I was the teacher and researcher, I was engaged in both the framing of activity structures and discursive practices in the classroom, and the data collection and analysis for this study. I had been a physics teacher for six years, all at the same high school, at the time of this study. I have an undergraduate degree in physics, a master's degree in education, and this study is my dissertation for the doctoral degree in curriculum and instruction.

I studied one of my ninth grade honors physics classes throughout a 12-day instructional unit on waves during the second semester. The class had 20 students (11 boys, 9 girls). I taught the class at a suburban public high school outside of Chicago. To enroll in ninth grade honors physics, students must have already successfully completed a yearlong algebra course. In this class of 20 students, there were: 13 Caucasians, four Asians, one African-American, one Hispanic, and one Indian. The students come from upper- to middle-class socioeconomic backgrounds, and live in a moderately affluent suburb of Chicago. The high school is 67.5% Caucasian, 11.9% African-American, 11.2% Asian or Pacific Islander, and 8.1% Hispanic.

Instructional Context

The study focused on a 12-day unit on waves outlined in Appendix. The unit began with students brainstorming different types of waves to activate their prior knowledge, and then enacting a human wave as a class to measure wave speed. The unit emphasized transverse waves, albeit introduced longitudinal waves, with the intention of bridging transverse waves with longitudinal waves during the following unit on sound waves. Over the course of the next several days, in teams of three, students conducted a series of experiments seeking potential relationships various wave characteristics had with wave speed using long metal slinkies. In between experiments, as a whole class, students presented, critiqued, analyzed, and discussed each other's findings. These experiments and activities allowed students to draw and discuss sketches of experimental setups and waveform graphs before the teacher modeled such representations, as well as use physical artifacts (long metal slinky and measurement devices). Students then began analyzing waveform graphs. First, they used the slinky setup from their experiments, but with a motion sensor, to graph the back-and-forth motion of a student's hand as they created waves in the slinky. Students suggested any relevant wave characteristics that they could measure. Later, other sources for wave production were considered from practice problems on which students worked in small groups. Next, they designed and carried-out an investigation concerning wave interference whose ideas were then applied to standing waves, which they studied for two days. On the last day of the waves unit, students conducted a lab practical that asked them in small groups to measure any wave characteristic for a bobbing mass on a spring, without any help from other groups or from the teacher.

Sources of Data

In order for me to collect data while simultaneously teaching, a video camera was used to record classroom interactions. Video data were collected from one of my ninth-grade honors physics classes over a 12-day instructional unit. Videotaping occurred each day for the entire 50 minutes for which the class met, five days per week. Each day's video was burned onto a DVD that I labeled and securely stored until the school year ended. The camera was positioned in the back of the classroom during whole-class activities and discussions. During small-group activities, one focus group (comprised of three students) was filmed by the students in that group. Students were informed of the purpose of the videotaping and told to “treat it like you were shooting a documentary.” I told them to consider the camera a team member that cannot speak but needs to be able to see and hear everything. The same focus group was followed for the entire duration of the instructional unit. There was no particular reason for the selection of this particular class to study over any of my other classes. I created the student groups, including group I focused on during small-group activities. My choice of students in the focus group was nearly arbitrary, except for ensuring that students were willing to talk as well as be comfortable videotaping and being videotaped. Students in the focus group were not selected based on academic status or performance.

One of the benefits of videotaping is the possibility it offers to repeatedly review the video to gain a higher level of delicacy, which is especially critical to research on multimodality where multiple modes may be used simultaneously, each with its own ideational, interpersonal, and textual metafunctions (Halliday, 1978). However, videotaping is a limitation too, as reliance upon a video camera’s recording may be problematic. Like any recording device, it can miss faint sounds, or visual information that is outside of the scope of the frame or too far away to be recorded sufficiently. What the camera cannot see or hear was lost for purposes of this study. Another limitation was that the videotaping during small-group activities was done by the focus group members themselves. They were not researchers and were not necessarily savvy video camera operators. To minimize this challenge, I gradually implemented the video camera to minimize the intrusive effects of its presence, and allowed for the focus group to grow accustomed to both using the camera and documenting their interactions appropriately. They were only vaguely familiar with the aims of my research, so they would not change their behavior to fit the study. I explained to them that I was studying *how* they learned, and that it was very important that they tape in a way that captured all aspects of their work–what they said, did, wrote, drew, showed, and so on. Of course, this did not guarantee that what they taped would allow me to capture all modalities at a given moment. In addition, during small-group activities, the video camera did not capture any communication or interactions of groups other than the focus group. Finally, immediately after each lesson, I wrote teacher-researcher reflections on noteworthy events, as well as my thoughts, comments, observations from that day's class, especially with regards to this study–the use and impact of different modalities on my teaching and my students' learning and engagement.

Analysis of Data

I used a qualitative, interpretive design to analyze the data of the study (Lincoln & Guba, 1985). More specifically, I utilized ethnographic and grounded theory techniques to analyze multimodal discourse to explore the multimodal landscape of my classroom and its culture with regards to concept development and multimodal engagement. The ways in which I analyzed the data provided me with insights into the cultural practices in my classroom in which I was also a participant. My insights from being an active participant were blended with those gained by systematically examining the classroom video data, as I examined the multimodality in my classroom and how it was enacted, and I mapped out participants' interactions and engagement with ideas, other participants, and artifacts within and across modalities to reveal the prominence of various modalities.

More specifically, I examined how the students and I called upon different modalities–our interactions within and about modes, semiotic features and grammar of a mode, and the potential affordances, limitations, and challenges that modalities offered to student learning and engagement. These interpretive considerations revealed general trends and themes over the course of the unit as well as more specific critical moments in the multimodal discourse that warranted a closer and more delicate analysis. This led to new ways of looking at the data, combining and recombining interpretations and themes (Creswell, 2012; Lincoln & Guba, 1985)

Using a grounded theory (Charmaz, 2006) analytical approach, I developed coding schemes that emerged from the data and were refined via iterative constant comparison (Miles & Huberman, 1994). Ways of thinking about multimodality were determined by the data as I noticed elements that were reoccurring or being absent (Corbin & Strauss, 1994).

The analysis unfolded as follows. After instruction was completed, I reviewed all of the data, formulating preliminary sketches of all of the videotaped lessons (the entire 12-day unit on waves). In order to construct these sketches, I first watched the video of each lesson as I created an outline describing the events that occurred, as well as noting preliminary interpretative comments regarding those events. I did this for all of the videos in chronological order. Figure 3.1 is a sample page of these preliminary sketches. My interpretive comments are in italics. These interpretations were made in light of the ideational, interpersonal, and textual functions of *multimodal* communication and, similar to my teacher-researcher reflections after the end of each lesson, highlighted the use and impact of different modalities on my teaching and my students' learning and engagement during each particular lesson.

Next, the teacher-researcher reflections I had composed immediately following each day's class during the unit were inserted into the preliminary sketches at the end of each lesson to unify these two datasets as the lesson sketches I would use for the rest of my analysis. Figure 3.2 shows a sample of these reflections. Both these reflections and the interpretive comments I wrote as part of the preliminary sketches were italicized as they both aimed at noting potential themes and patterns regarding meaning making and multimodality that I could monitor and track over the course of the unit. My goal for developing these lesson sketches was to outline the events that occurred and code categories that emerged in my comments, reflections, and interpretations of the data (Charmaz, 2006).

The data were analyzed repeatedly through multiple rounds of coding in which I reduced the data and recombined it according to categories that represented themes and patterns I noticed (Creswell, 2012). These initial categories included participants' negotiation of a particular modality's grammar, benefits or limitations of modes to the clarity of communicative units, ideational links between modalities, shifting between modalities, participant-choice of mode(s), and foregrounding (and backgrounding) of modes. These categories were not mutually exclusive and often overlapped in both data and content. The same event could be coded as relevant to multiple categories, and some categories could be considered as subcategories of others. For example, the category defined by instances where modalities seemed to benefit or limit the classroom discourse often encompassed some of the other categories, such as shifting between modalities or ideational links between modalities, since both of these represent ways in which modalities were used by participants benefitting or limiting the classroom discourse.

2/22 - Sketch: Definition of waves/intro to experimenting with waves

Q- What are waves transferring; what is actually moving?

- Bell Work
    - Fixed Camera on tripod in back of room
    - Instructions projected in front as text
    - Teacher verbally explains the instructions
        - *The two modes complement one another? But the one aspect that was spoken ONLY verbally was missed by Ju (see 1:50) when she was confused about the instructions*
    - Students talk with one another and begin to work (some talk about waves but inaudible and some talk off task)
    - 1:03 T turns on lights
    - 1:20 Em & C look for affirmation
        - Em says "like water" and makes a undulating hand gesture
            - It is this hand gesture that the T wants her to draw
            - *The modality transfer in this case would appear to begin as abstract cognition about waves that is solely based on prior experience (i.e. what comes to mind when you think of a wave?), then this idea transfers to a gesture (undulating hand coupled with speech about the motion(undulation) and example (water)), which then is to be transferred to a visual-pictorial mode through their own production*
        - T responds vaguely – do whatever you think is right
    - T collects the BW's
- Lights off –signals beginning of discussion
- 7:15 T begins BW discussion
    - 8:00 T explains purpose of BW: "What do you see in your mind when someone says 'wave'?"
        - T says to hide WB's (models for them) and make a circle
- Lights on
- WB gallery view
    - 9:00 WB's are unveiled to each other
    - T looks for other who did what he did (wavy line)
        - *T-led speech about the focal objects (drawings on the WB's)*
    - 9:26 Br says tidal wave and makes a undulating hand gesture
    - T talks aloud as he looks for patterns in the student WB's & focuses classes attention to different WB's (Ju –Ba-D-K-Ell-Em)
        - Emily (sound waves) (ripple idea)
    - T asks for any others
        - Students being shouting out types of light (radiowave, ultraviolet, infrared, microwaves) which are not drawings but instead vocabulary terms they recall from previous science courses in primary school
            - T does not comment on their verbal suggestions and ends the activity…students return to their seats
- Lights off
- T summarizes the WB gallery view by drawing the 2 common drawings observed
    - T explains purpose of activity to this point and next activity
    - T draws a wavy line and makes a undulating hand gesture that follows the line
        - ***Linking modalities***- *This was unintentional linking of the emergent undulating hand gesture with the wavy line drawing*

Figure 3.1. Sample page of preliminary sketches.

2/22 – intro to waves

Reflection (over Bell Work completion):

- ***Visual & textual (T-intended), verbal (emergent, peer-peer),** - I had them answer the 3 questions mentioned above, as well as draw the wave (#1) on a little whiteboard. There was a lot of informal verbal exchanges & interactions during this process, especially between Cassie and Emily (focus group). They were very hyperactive during this task.*
- *Many students expressed verbally that they didn't know if they were doing it right, and I noticed that many of them skipped the answering #2 initially. This might be a result of a couple reasons: (1) that this is the most difficult question of the three, and/or (2) that a definition of a wave can be derived from the responses to #1 & 3—draw and think of examples…now what do they have in common that might make something a wave.*

Reflection (over T-led class presentation of wave drawings on little whiteboards)

- ***Drawing, verbal**- Students made a circle to present their whiteboards to each other. They were very off task and the teacher had trouble focusing everyone's attention. The camera could not see everyone's board, but most had the sinusoidal picture, with some showing 2 or three different diagrams. The similarities between many of the students' whiteboards as well as the amount of talking during the drawing process would suggest that many students took ideas from one another*
  - *I quickly left this activity after highlighting the 3 variations I observed, asking some students to verbally elaborate on their depictions*
  - ***Textual (secondary to visual)**- Some students wrote words such as "sound", or "radio"*
    - *Some students have seen the sinusoidal waveform from math class (trigonometry) if they are higher level math*

Reflection (over T-led class discussion of Bell Work responses)

- ***Visual, verbal**- T draws the sinusoidal and ripple versions*

  - *Tasks students to explain how these two diagrams are different, or the same.*
    -
  - ***Verbal**- Students use water waves as part of their explanation, they mention specific details such as "one has up and down motion where the other moves away"*
    - *Students can focus on the macro or micro perspective of the wave from these diagrams [i.e. back and forth motion (pulse) vs. the propagation of the pulse]*
      - *Students highlighted both of these perpectives, starting with propagation, then the pulse, when commented that the right diagram is a view from above.*
      - ***Gesture (emergent, foregrounded head of verbal)**: Brandon motions in and out as he tries to find words to explain the motion of the source creating the ripple diagram.*
        - *T uses this motion and adds the words "in and out" to help the struggling student and bring the verbal back to the foreground with the gesture (to link them)*
- *Tasks students to volunteer their responses to #2*
  - *There is a lot of confusion, talk of energy and what makes up a wave (much of it is student talk and the teacher is merely trying to maintain some coherence and order without getting in the way of the flow of conversation. Many students begin to ask questions about waves.*

· crest
trough

* moves away
from a source
i.e. a repeating pattern
(back & forth
motion)

* repeated, back & forth motion
that is sent through a
material!

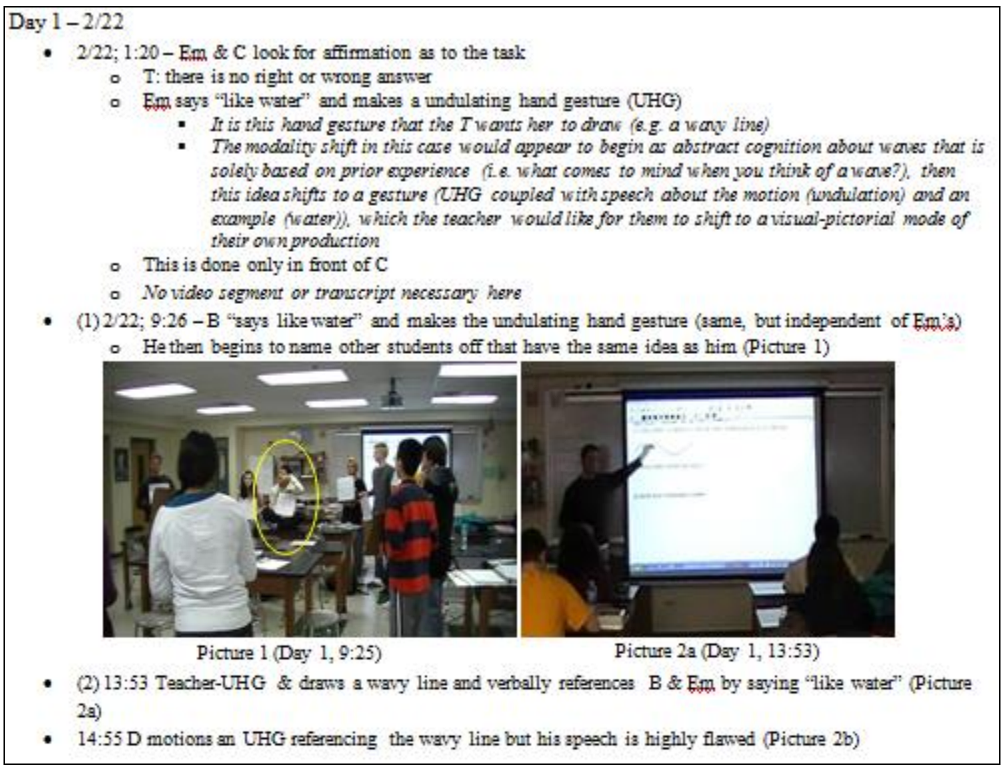
3

Figure 3.2. Sample page of teacher-researcher reflections.

After coding, I then reviewed the sketches again for each of the following modes that were most prominent throughout the unit: gestures, diagrams, numerical values and data tables, and graphs. Each respective mode served as a distinct and separate lens for reviewing the sketches. I examined the sketches and gathered and demarcated video clips of the segments where I found a particular mode to be prominent in the classroom discourse. These segments were extracted from the lesson video-recordings into separate files that were labeled according to what they captured and sorted by modality as well as when they occurred. From each video segment, I also extracted digital still photos of specific instances to use as figures in the presentation of my findings as videos cannot be inserted into written documents. For each video segment and still photos, I also wrote a more detailed description with interpretative comments that were used to develop an outline for a particular modality, as seen in the sample in Figure 3.3. I then reviewed these outlines and elaborated on my interpretations while looking for salient themes that emerged within that particular modality. During this review, I also identified which video segments I should transcribe and revisit with a higher-level delicacy for my analysis.

Two modes emerged as prevalent: gesturing and diagramming. Gesturing and, in particular, iconic hand gestures were a prominent and consistent mode for meaning making among class participants and their meaning evolved over time as my students and I used them. Diagramming was also a pronounced modality utilized often by both teacher and students. These two modalities, therefore, became parts of my findings that focused on the evolution of form and function of modalities in science teaching and learning.

While examining, sketches, outlines, and video for meaning making using each modality, I noticed overlap between modes regarding particular ideas or thematic patterns with which my students and I were engaging throughout the unit. I, thus, tracked the evolution of two major thematic patterns across various modes that emerged from the data. These themes reflected two of the major concepts I intended for students to learn as part of this unit on waves: (1) learning about relationships between various wave characteristics through their experimental investigations so that they understand that only a wave's medium affects its propagational speed, dispelling the pervasive misconception that the source of wave can influence the wave's speed; and (2) understanding and measuring wave characteristics, and especially in regards to waveform graphs. These two themes, thus, became parts of my findings that focused on concept development in the context of multimodality.



Day 1 – 2/22

- 2/22; 1:20 – Em & C look for affirmation as to the task
  - T: there is no right or wrong answer
  - Em says "like water" and makes a undulating hand gesture (UHG)
    - *It is this hand gesture that the T wants her to draw (e.g. a wavy line)*
    - *The modality shift in this case would appear to begin as abstract cognition about waves that is solely based on prior experience (i.e. what comes to mind when you think of a wave?), then this idea shifts to a gesture (UHG coupled with speech about the motion (undulation) and an example (water)), which the teacher would like for them to shift to a visual-pictorial mode of their own production*
  - This is done only in front of C
  - *No video segment or transcript necessary here*
- (1) 2/22; 9:26 – B "says like water" and makes the undulating hand gesture (same, but independent of Em's)
  - He then begins to name other students off that have the same idea as him (Picture 1)

Picture 1 (Day 1, 9:25)

Picture 2a (Day 1, 13:53)

- (2) 13:53 Teacher-UHG & draws a wavy line and verbally references B & Em by saying "like water" (Picture 2a)
- 14:55 D motions an UHG referencing the wavy line but his speech is highly flawed (Picture 2b)

Figure 3.3. Sample page of a modality (gesture) outline.

For each of the four themes, I used all data forms, sketches, video segments, and digital stills, to produce a theme outline. The video segments that captured interactions that had particular significance or required more detailed analysis of the multimodal discourse were, then, transcribed and analyzed.

To capture the multimodal classroom discourse in the transcription of video segments, I used traditional sequencing of verbal utterances along with description of non-linguistic features related to both the manner in which the speaking occurred as well as multimodal aspects. To further capture multimodal aspects, I inserted digital stills from the video segments alongside the transcribed units that displayed the non-linguistic modalities such as gestures and diagrams. The multimodal transcript had two columns: one consisting of the verbal utterances and my description of multimodal information, and one consisting of digital still photos arranged in such a way so that they were located adjacent to the linguistic discourse that occurred at the same time.

Constructing multimodal transcripts was imperative in order to capture the power of the various modalities used in my classroom as my students and I worked together towards developing meanings about waves. However, there are limitations to examining multiple modalities. Utilizing a picture as a focal object activates different experiential meaning potentials (Kress & van Leeuwen, 2001), and offers interpretive flexibility (Roth, 2005). In this light, meaning making is much more in the eye of the beholder when interpreting images or diagrams, for instance, than when interpreting a verbal unit. Thus, interpretational agreement among researchers, the researcher and creator of multimodal acts or representations, and the researcher and audience may be difficult to achieve. I confronted this challenge by expecting and embracing it, as it was actually an impetus for my study. The interpretive ambiguity, that different modalities foster, influences student learning and engagement. Each modality has strengths and weaknesses in conveying a particular message, idea, or concept. Thus, multimodality in teaching and learning balances limitations across different modalities and strengthens meaning making and communication. Moreover, as students learn how to engage in multiple modes and their ideational, interpersonal, and textual functions, learning of the concepts about which they interact also takes place.

IV. EVOLUTION OF THE FORM AND FUNCTION OF MODES

Undulating Hand Gesture

Gesturing played a critical role in the teaching and learning of physics, and particularly waves on which I focused in this study. In my classroom, an undulating hand gesture (UHG) bubbled up from the students on the first day of the instructional unit. This enactment spontaneously emerged and quickly became an insightful iconic gesture that both my students and I called upon repeatedly throughout the entire unit. The UHG originated as an undulating up-and-down hand gesture representing a water wave. As the unit continued, the students and I frequently used the UHG in different ways that shaped the gesture's meaning, function, usefulness for meaning making, and even slightly its form.

The Construction of a Hand Gesture and Its Role in Meaning Making

There were two types of undulating hand gestures that took place in my classroom that both share oscillatory aspects. The UHG began as an enactment of a wave's sinusoidal shape and the undulation that occurs during its propagation. The other gesture consisted of a simple back and forth motion of a hand or back-and-forth gesture (BFG). This gesture emerged later as students created waves in a slinky and discussed the ways in which they created waves. This movement back and forth was a shift from the back and forth sinusoidal undulation of the original gesture. Although these two gestures differ to some degree in form and function, they represent similar underlying concepts and are generally two representations of the same phenomenon–the particle motion of waves.

The UHG emerged on the first day of the unit from a student, Addy, who was seeking affirmation around the task the class was to be working on–to draw a wave (see Appendix for an outline of the instructional unit). She asked "like water?" as she gestured, suggesting that she envisaged the up-and-down motion of water waves as she drew a wave. Addy's gesture occurred while the students independently worked on the task and was not made public to rest of the class. Her gesture may have referenced an image of water waves undulating that she was about to draw. She was not alone in associating waves in general with the more specific example of water waves. Brian made an identical UHG minutes later during a discussion in front of the class, seen in Figure 4.1.1. The time in the captions of all figures refers to the time passed from the beginning of class.

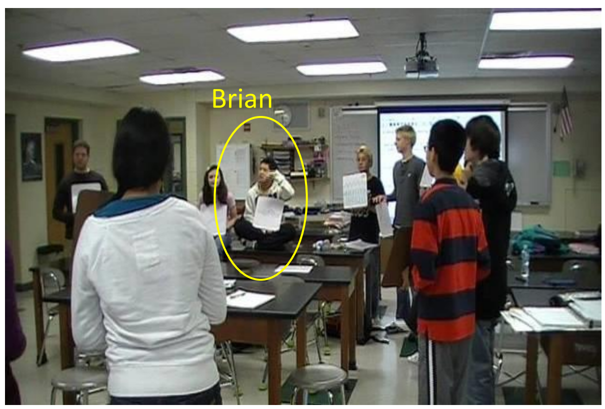


Figure 4.1.1. (Day 1, 9:25). Brian makes an UHG and says "like water" to the rest of the class.

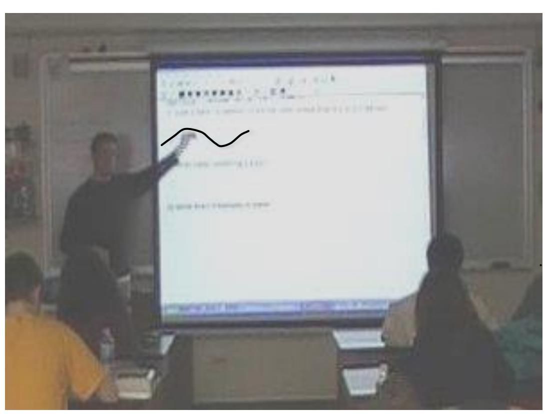


Figure 4.1.2. (Day 1, 13:53). I superimpose an UHG on top of the wavy-line drawing.

Brian also said “like water” as he gestured in the same way as Addy, but never heard nor saw Addy’s original gesture. The circular arrangement of students in the classroom seen in Figure 4.1.1 is important because the entire class could see the wavy lines Brian drew on the little whiteboard he was holding. They could all hear his speech see his UHG, which together represented his idea of a wave. The public nature and ease of visibility that the circular arrangement of students afforded allowed these modes to be foregrounded for the other students so that they could potentially draw upon both these modes to think about waves in future class interactions. Moreover, I noticed the prominence of the UHG as my students kept using it and, thus, aimed at building the gesture into my teaching to promote its usage and development.

Immediately following the whole-class discussion, I summarized the students’ findings and conclusions in a lecture format where I attempted to link the wavy-line drawing that many students suggested with the UHG. To do so, I superimposed my UHG over the wavy-line drawing to suggest that the UHG was an enactment of the wavy-line drawing (see Fig. 4.1.2), and then verbally referenced the water analogy presented earlier by Brian and Addy. I intended to reinforce the UHG as a means for enacting the back-and-forth nature of waves in general, which was a fundamental concept about waves that students needed to develop throughout this unit. I put into practice my multimodal awareness by first recognizing the emergence of a potentially valuable gesture, and then promoting it to my class in order to collectively develop its function in hopes that students will continue to use the gesture.

Gestures often functioned as a convenient modality for students particularly when they struggled to articulate their ideas using speech alone. For example, in Figure 4.1.3, Dustin made an UHG as he offered his interpretation of the projected diagrams, stating, “the one on the left goes up and down and the one on the right like goes out.” His speech about waves was muddled and vague, and it was unclear from this utterance whether or not he had a meaningful conception that he was trying to communicate at that moment, but he used an UHG as he spoke to help articulate his idea that he struggled to explain by talking alone. The UHG was an iconic gesture that both referenced and enacted his interpretation of the motion depicted in the drawings ("up and down," or "goes out"), which he was attempting to use to explain how these drawings were different.

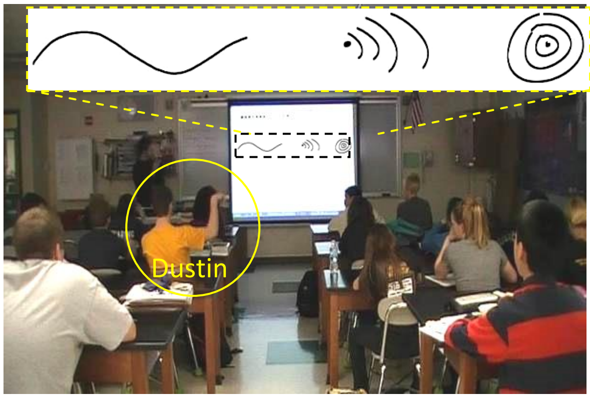


Figure 4.1.3. (Day 1, 14:50 or 14:55). Dustin makes an UHG along with muddled speech.

All of the different types of wave drawings offered by the students were projected onto the screen, shown in Figure 4.1.4. After asking for students to volunteer their interpretations in front of the class, Oliver suggested that the "ripple" drawing (i.e., the concentric circles on the right in Fig. 4.1.4) was a view from above whereas the wavy-line drawing on the left was a view from the side of a wave. I revoiced Oliver's idea by verbally describing the motion as "in and out" and "bobbing," while simultaneously patting the screen with my hand at the center of the ripple drawing as seen in Figure 4.1.4. I did this in an attempt to link these drawings to one another as different representations of the same concept by using a BFG. I also recognized that my students would be creating waves in a long metal slinky during the activities in the days to follow, and provided a potential connection for students by shifting from the UHG as an enactment of the sinusoidal nature of waves to a stationary bobbing motion at the origin or BFG, which would later represent one's hand-motion while creating waves in a slinky. I aimed to promote this new BFG with hopes that my students would call upon it as they developed new ideas and concepts about wave characteristics.

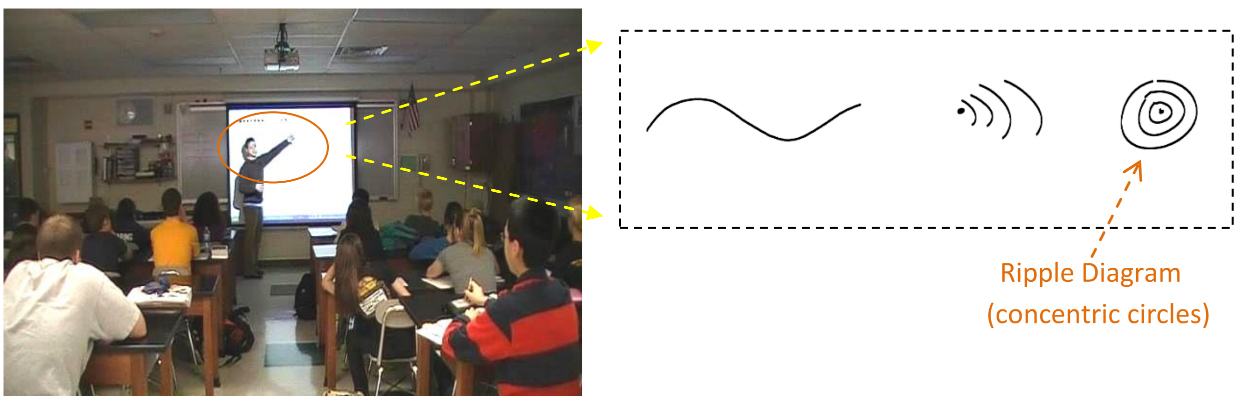


Figure 4.1.4. (Day 1, 14:55). I project the three different variations of student-drawings of waves onto the screen in front of the class. I pat the screen at center of the "ripple" diagram (concentric circles) to change the perspective from a *side* view of a wave (the wavy line) to an *above* view of a wave (concentric circles).

Still in the first day of the unit, my students continued to use the UHG to call upon their prior knowledge of waves from their middle school science classes, as well as their current mathematics classes in which several of the students had already learned about sinusoids. Figure 4.1.5 shows Zeke and Addy both making an UHG as Zeke says, “it’s like a cosine graph.” Although Zeke was the one speaking, Addy nodded her head saying “yeah yeah” in agreement. At the same time, she independently traced a sinusoidal function in the air using a similar gesture to original sinusoidal UHG, but without seeing Zeke’s gesture. Zeke and Addy’s use of the UHG indicated a possible linking of the wavy-line drawing in this class to sinusoids that they were studying in their mathematics classes. Both Zeke and Addy were concurrently enrolled in Algebra 2 in which they had just finished a unit on wave functions and sinusoids. Zeke’s linking the drawing of waves to drawing to “a cosine graph” was mediated by his gesturing, which added motion to the visual depictions (wavy-line and cosine graph) that Zeke used along with his talk.

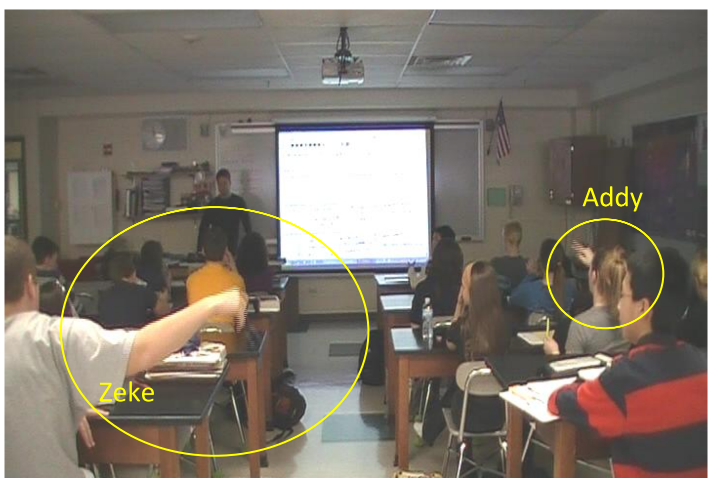


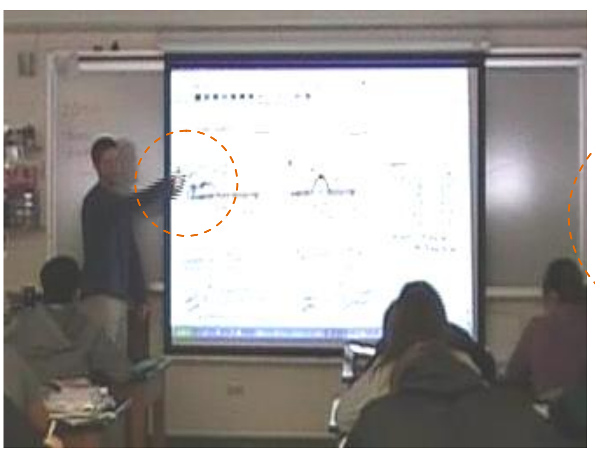
Figure 4.1.5. (Day 1, 37:55). Zeke and Addy both make an UHG as Zeke says, “it’s like a cosine graph.”

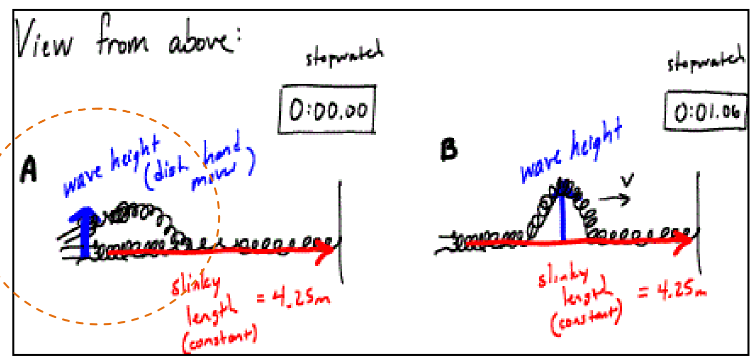
Through its prominence during the first day, the UHG had already been a useful tool that as the teacher I considered in my planning and decision-making for the rest of the unit. I thought that both my students and I could be utilized it in the development of new ideas about waves. One such new idea was relating the UHG's sinusoidal undulating characteristic to the BFG's oscillatory nature of a wave's source.

During Day 2 (see Appendix), each team of three students conducted an experiment testing the relationship between a wave's height and its propagational speed, which involved the creation of wave pulses in a long metal slinky. The experiment provided a new context for the BFG where the back-and-forth hand movement was now used to generate a wave pulse. This helped students begin to link the UHG to the BFG through the use or manipulation of artifacts. In Figure 4.1.6, Katie made a wave along the floor to demonstrate to her peers her interpretation of the wave's height and how to change it. She used a wide sweeping motion to demonstrate how she could create a larger wave height. In this example, the BFG while holding a slinky enacted the wave's height, which could be varied by how large of a BFG Katie made.

During the follow-up lecture on Day 3 that summarized the previous day's experimental findings (see Appendix), I superimposed a BFG over a diagram to call attention to the hand-motion the students had used to make waves in the slinky with hopes of their linking this motion to the diagram. I was using the BFG to facilitate their creation of such a link (see Fig. 4.1.7), as well as to attach additional meaning to the BFG, namely that it can create waves or function as a wave source, which I hoped for students to take up and bring out during future interactions.

Figure 4.1.6. (Day 2, 00:25). Katie makes a wide sweeping wave on a slinky along the floor to show how the wave's height can be changed.





Notes from picture on left

Figure 4.1.7. (Day 3, 04:06). I move my hand up and down as seen on the right of the image marked by the dotted circle.

I then aimed to extend the BFG role in creating waves to the context of waveform graphs. In Figure 4.1.8a, my bottom hand remained stationary to mark the equilibrium position while my top hand oscillated up and down about the equilibrium position as an enactment of how I could create the wave pictured in the notes. This gesture, coupled with the accompanying text: “wave height same as the source’s back-&-forth movement,” written just below the diagram called students’ attention to the BFG in relation to the diagram as an attempt to anchor the new concept of amplitude to a familiar experience (wave-creation in slinky). I superimposed the BFG onto the diagram in the same way I did earlier with the slinky-experiment diagram (wave-creating role shown in Fig. 4.1.7), and then moved my hand with the wave, as seen in Figure 1.8b, to also link it with the UHG that emerged in Day 1 (see in Figures 4.1.1-3).

During a whole-class discussion later that day (Day 3 in Appendix), some students were able to demonstrate how the BFG could function as a wave source when they applied it to the new concepts of *period* and *frequency*. At this point, my students had not yet studied these concepts nor had they been introduced to these terms. Reference to these concepts occurred when both Addy and Oliver briskly moved their hands back-and-forth while referring to the *quickness* of a pulse, which they introduced to the discussion as a possible characteristic that might affect the wave’s speed. Both the word “quickness” and the BFG at that moment were ambiguous in terms of whether they referred to time or speed of the motion source. Addy and Oliver may have meant that the amount of time that it takes for the hand to go one full back-and-forth movement (i.e., the wave period) influences the wave’s speed, or they may have meant that the hand’s speed influence the wave’s speed. This is a critical distinction, which is usually linked to misconceptions that students have about waves and factors that determine their speed, and which implies different ways of testing for factors that affect wave speed. Although such a distinction was not made at this point, the BFG offered students an opportunity to focus on wave period, as it will be shown below.

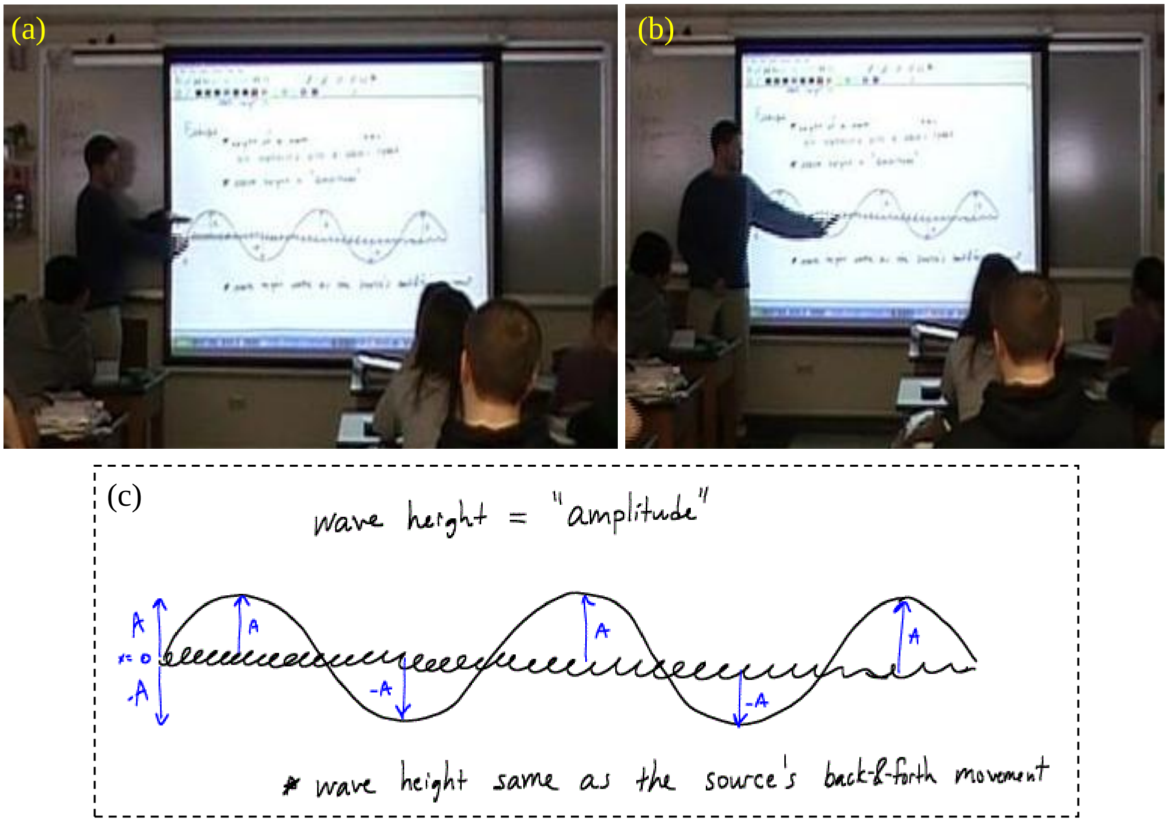


Figure 4.1.8. (a), (Day 3, 18:34). My bottom hand is stationary and marks the equilibrium position while my top hand oscillates up and down about the equilibrium position to show how the wave pictured was created. (b), (Day 3, 19:02). My UHG traces along the wave pictured. (c), Enlarged view of the part of the whiteboard on which I am focusing.

Immediately following Addy and Oliver's suggestion that the quickness of the hand might affect a wave's speed, students collaborated in their teams on an experimental setup that might determine this relationship. We then came together as a class and Raymond was elected to sketch his team's idea that was specifically related to a method for measuring the quickness of one's hand in making a wave pulse in a slinky. Figure 4.1.9a shows his sketch of the experimental setup. It included a slinky and a motion sensor that was aligned with the hand's line of motion.

Raymond’s diagram positioned the orientation of this back-and-forth action in relation to the artifacts (motion sensor and slinky). After drawing the slinky and motion sensor, he drew a hand at the bottom of the slinky, while saying, “here’s a hand.” He then drew a horizontal line from the hand away from the motion sensor, and inserted a positive sign underneath it saying, “and it goes positive,” and then drew another line from the hand towards the motion sensor, and labeled it with a negative sign saying, “then negative.” The positive and negative lines depicted the hand’s movement away from the motion sensor (positive direction), and back towards the motion sensor (negative). The overall motion of the hand is not clear from this diagram, but the sequence in which he diagrammed the lines and explained suggested that he considered the hand to first move away and then toward the motion sensor. The BFG in relation to his diagram seemed to enact the hand’s motion iconically (see Fig. 4.1.9c) demonstrating the hand’s motion in creating a wave. In this case, the BFG was being used to move one end of the slinky from side to side, which would create a wave pulse in the slinky. Although Raymond did not gesture while diagramming, his sketch built on his understanding of the BFG as a wave source by diagramming it with regards to artifacts, while his speech narrated the actions depicted in the diagram.

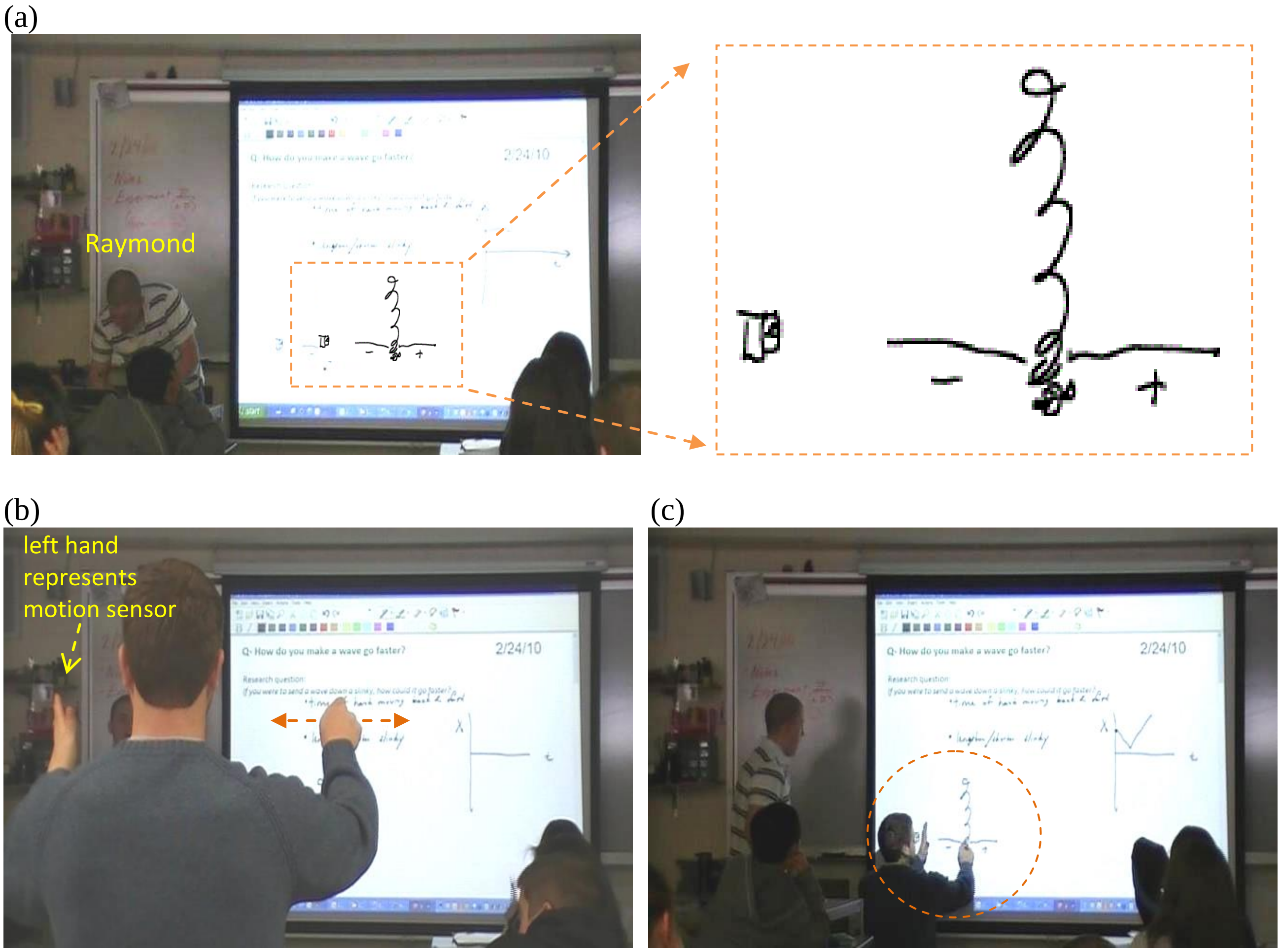


Figure 4.1.9. (a), (Day 3, 19:02). Raymond's drawing of an experimental setup that might be used to measure the time of a hand's back and forth movement during wave production. (b), (Day 3, 27:20). My flat left hand represents the motion sensor, the right hand (which would be holding a slinky) moves left to right in front of the sensor. (c), (Day 3, 28:28). I superimpose the same gesture from Figure 4.1.9b on top of Raymond's diagram.

Raymond became confused when asked to sketch his expectation for the computer-generated graph of the motion sensor's position versus time data, which I will abbreviate as the "motion sensor's graph" in the rest of this manuscript. The motion sensor is a device that simultaneously collects position and time data for any object in front of it, relative to the motion sensor's position. The motion sensor is part of a computer interface whose software plots the data on position versus time axes in real time. After drawing position and time axes next to his diagram, and naming the axes verbally as he drew them, Raymond hesitantly began to draw its curve as a horizontal line corresponding to a positive position value, while saying, "it goes like, uh, um." He stopped talking and drawing, and said that he wasn't sure. In response to Raymond's confusion, I used a BFG as a means of scaffolding his thinking (Fig. 4.1.9b). My left hand represented the motion sensor and my right hand, which would be holding a slinky, oscillated left and right in front of it. As Raymond tried to draw the curve again, he sketched a negatively sloping line beginning at a positive value, followed by positively sloped line thereafter (see free-hand graph in Fig. 4.1.9c). My BFG mediated Raymond's thinking within the graphical mode by articulating the specific hand motion that the sensor was capturing, which helped Raymond to translate to the shape of the graph's curve that he drew. His drawing of a horizontal line and confusion might have derived from his uncertainty as to when the motion sensor would begin plotting position and time data. If the motion sensor had begun collecting and plotting data before the hand made a full back and forth movement, it would start off in the shape Raymond initially drew. He might have been unsure of whether or not to include this and which way, positive or negative, the line should move. My BFG helped him to decide to begin drawing the motion sensor's graph when the hand starts to move, and additionally, and to chose to have the hand move towards the sensor and then back as depicted by the graph. I recognized then that my BFG had helped him translate the motion to the graphical modality, and to promote this connection for the rest of the class, I walked up to the screen next to his diagram and superimposed my BFG over the top of the diagram, as seen in Figure 4.1.9c. My original BFG (Fig. 4.1.9b) was made in the back of the room, which might not have been observed by all of the students, but more importantly, my superimposing a BFG over Raymond's diagram (Fig.4.1.9c) directly connected it to the diagram, and more specifically, the artifacts depicted in his diagram. My efforts aimed to explain the idea of period and frequency in relation to the quickness of the BFG that created a wave in a slinky, which was a concept that I wanted my students to call upon when appropriate during future lessons.

This was the case the next day (Day 4) when Addy used the quickness of a BFG, which she made in the air, as she sought affirmation for how to measure the period during the second slinky experiment (see Appendix) where the students were to explore the relationship between a wave's period and propagational speed using a slinky. As the focal group reviewed their motion sensor's position vs. time graph of the hand's motion, Addy asked, "we're measuring the time it takes our hand to move from here to here?" The synchronization of her utterance with her gesture suggested that the "here to here" marked the interval between when her hand began to produce a wave pulse and when it returned to its original position, thus completing one full back and forth motion. This showed that she understood that the wave's period, which students were to measure as part of this slinky experiment, was the time interval for one's hand to move back and forth as depicted graphically by the motion sensor. Moreover, her question and deictic gestures sought to affirm a collective agreement as to which two points on the graph were associated with the beginning and end of her hand's back and forth motion.

On Day 6 (see Appendix), I set up a slinky along the floor in the middle of the class with which I led a demonstration in front of the class that would use the same context as their slinky experiments, but aiming to introduce waveform graphs. A significant difference was that, in this demonstration, continuous wave pulses were generated instead of just one pulse, which was the case in the students' slinky experiments. I had a student, Mallory, make continuous waves on the slinky while a motion sensor captured her hand's motion (BFG) and plotted the corresponding position-time graph that was projected on a screen in front of the class in real-time. With this activity, I built upon the BFG that students and I had used to call attention to the distance and time of the back-and-forth motion of one's hand as it created waves in a slinky. Wave-form graphs were new to these students and I was aiming to connect these graphs to students' familiar prior experiences with slinkies and previous concepts of amplitude and period. This demonstration shared similarities with their previous two slinky experiments, namely the same artifacts (slinky and motion sensor) and experimental setup that were used for generating waves, and involved the concepts of period and amplitude of waves created by a BFG.

The task following the demonstration prompted students to apply these concepts of amplitude and period to the continuous train of pulses and the graph produced by the motion sensor. The task asked students to obtain values of any wave characteristics possible. In this way, I wanted to find out whether students could identify other relevant characteristics that could be quantified. Such wave characteristics may include wavelength, frequency, or wave speed by calculating the wavelength divided by the period. After working in their teams for several minutes, I asked Brian to describe a wave characteristic his team was able to measure. Figure 4.1.10 shows how Brian made a quick BFG by using the laser pointer to trace along the curve from a trough to the next crest and back to the next trough where the same pattern would be repeated. This demonstrated his understanding of the seeing one wave cycle on the motion sensor graph. This is significant because he started at the trough and traced up to the crest and back down to the following trough, which corresponded to the hand motion that initially moved to the left (toward the crest) and then to the right as it returned to where it started (back down to the trough). In his speech, he linked one wave cycle on the graph with the concept of period, saying: “we did the time between the uh, the time for uh, to produce one wave, and our time was 0.2 seconds because it took about 0.2 seconds to create one wave.” I sought more elaboration by asking Brian to show one complete wave cycle on the graph. He replied, “because for every motion [Mallory] does, it creates one wave, so this would be one wave [traces graph from trough to trough in same way as seen in Figure 4.1.10] and this would be one wave [traces next wave cycle from trough to trough] and so on.”

Four modes (gestural, artifactual, graphical, and linguistic) were all in use providing opportunities for meaning making for Brian and the rest of the class. Brian’s speech and gesture provided his peers and me access into his ideas, which were scientifically accurate. His definition of period as “time for one wave” was based on his definition of one wave, which is why I asked him to clarify what he meant by one wave graphically using the laser pointer. His talk while using a laser pointer to trace one wave cycle on the graph allowed him to successfully transduct the concept of one wave cycle between the artifactual mode by referencing Mallory creating the slinky wave, the BFG (i.e., enacting the motion of Mallory’s hand using a BFG), and the graphical modality by tracing one full wave cycle on a waveform graph. Moreover, he used the time axis afforded by the graphical modality alongside his recognition of one wave cycle on the graph to quantify the period of the wave.

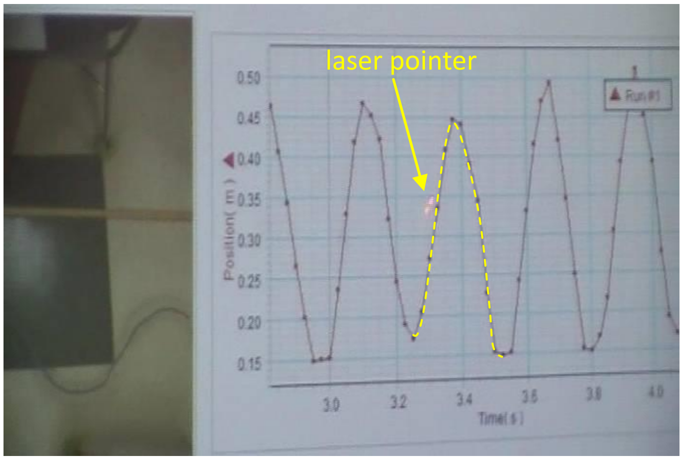


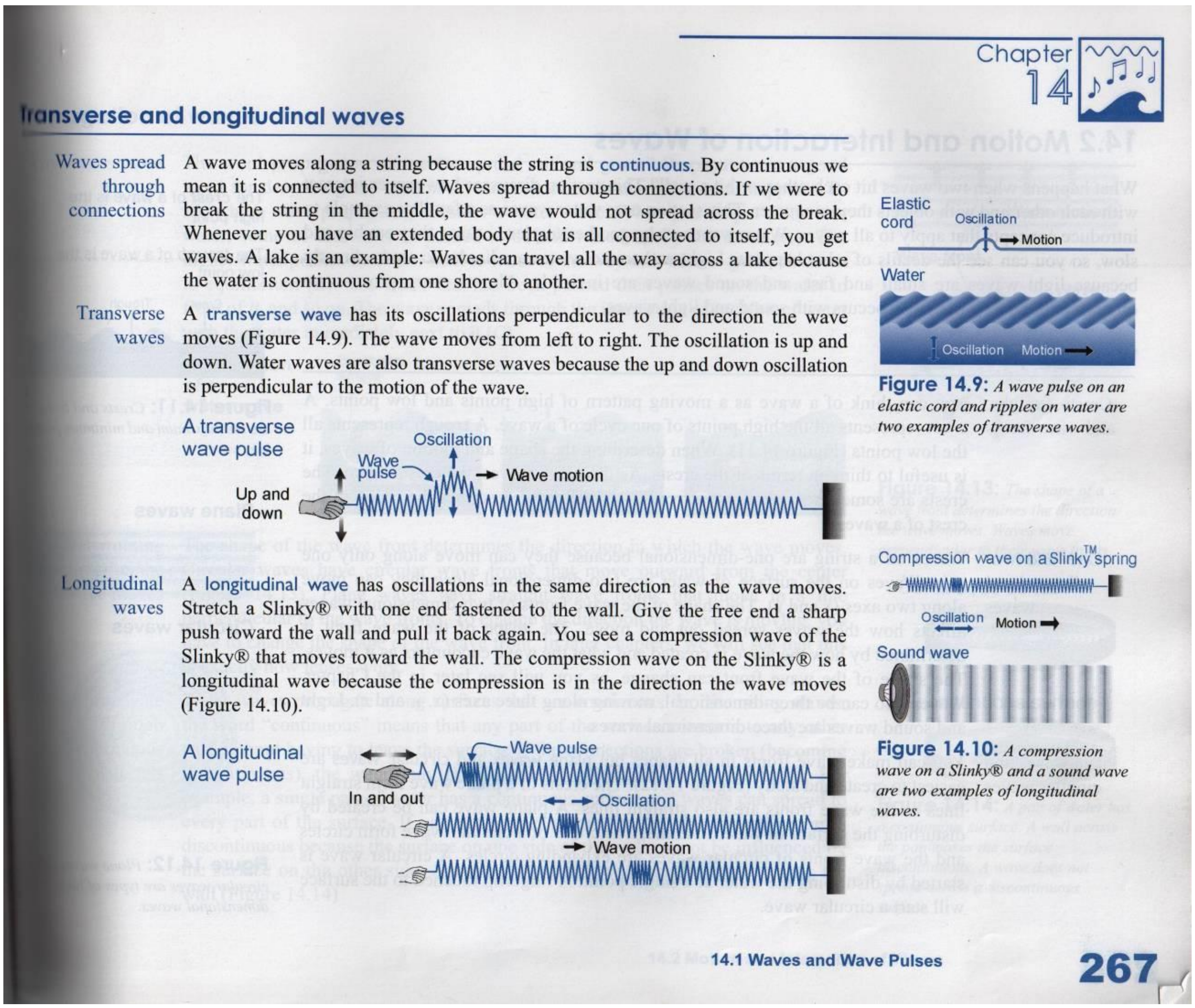
Figure 4.1.10. (Day 6, 15:26). Brian uses laser pointer to trace out one full cycle on the waveform graph. The dotted line denotes the path Brian traces with the laser pointer.

Later in the same activity, Mallory moved her hand up and down as if she were creating a wave (i.e., made a BFG) in relation to the waveform graph to define one wave cycle and the period (Fig. 4.1.11a). The difference in the BFG used here by Mallory and the one that Brian made earlier was that her BFG had an undulating form to it, and, thus, transformed into a combination between a BFG and a UHG–an up and down hand movement that was propagating to the right. The BFG was now being connected to the curved sinusoidal shape of the graph, and in doing so, was taking on an undulating characteristic to resemble the line's shape. I further explicated this link between referencing the creation of waves in a slinky through a BFG to the UHG's referencing of the sinusoidal shape of the waveform graph by deictically gesturing to the specific points on the waveform to which Mallory referred with her iconic hand gesture. As seen in Fig.4.1.11b, I made the same gesture as the one she made from her seat; however, my gesture was made on top of the waveform graph while I deictically pointed out the beginning and ending points for one wave cycle. My gestures occurred simultaneously with Mallory's speech as I tried to superimpose her speech and gesture with my own gestures.

Figure 4.1.11. (a), (Day 6, 16:07). Mallory uses a combination of a BFG and UHG in relation to the waveform graph to define one wave cycle and the period by moving her hand up and down as if she was creating a wave, but also showing the propagation of the wave. The motion of her hand is shown by the dotted line. (b), (Day 6, 16:20). I repeat Mallory's gesture by deictically gesturing to points on the projected waveform graph corresponding to the points Mallory was describing from her seat.

On the following day (Day 7), the students worked in their teams on practice problems. The focal group, including Zeke, looked up the new term "longitudinal" in their textbook after they noticed it in one of the practice problems. The textbook page they reviewed is seen in Figure 4.1.12. After reading this page, Zeke summarized it to his peers, saying "oh this is when you go like that," while simultaneously gesturing as if he were creating a wave in the slinky by moving his hand forward and backward instead of side to side (Fig. 4.1.13a). Here, Zeke used a

BFG as a means of enacting the textbook's textual and diagrammatic definition seen in Figure 4.1.12. Since the BFG was already a familiar aspect of the class's multimodal discourse and carried meaning in relation to wave production and analysis, Zeke easily appropriated the textbook's explanation using the BFG and used the gesture in his explanation of the term to his peers.


Chapter 14

Transverse and longitudinal waves

Waves spread through connections — A wave moves along a string because the string is continuous. By continuous we mean it is connected to itself. Waves spread through connections. If we were to break the string in the middle, the wave would not spread across the break. Whenever you have an extended body that is all connected to itself, you get waves. A lake is an example: Waves can travel all the way across a lake because the water is continuous from one shore to another.

Transverse waves — A transverse wave has its oscillations perpendicular to the direction the wave moves (Figure 14.9). The wave moves from left to right. The oscillation is up and down. Water waves are also transverse waves because the up and down oscillation is perpendicular to the motion of the wave.

Figure 14.9: *A wave pulse on an elastic cord and ripples on water are two examples of transverse waves.*

Longitudinal waves — A longitudinal wave has oscillations in the same direction as the wave moves. Stretch a Slinky® with one end fastened to the wall. Give the free end a sharp push toward the wall and pull it back again. You see a compression wave of the Slinky® that moves toward the wall. The compression wave on the Slinky® is a longitudinal wave because the compression is in the direction the wave moves (Figure 14.10).

Figure 14.10: *A compression wave on a Slinky® and a sound wave are two examples of longitudinal waves.*

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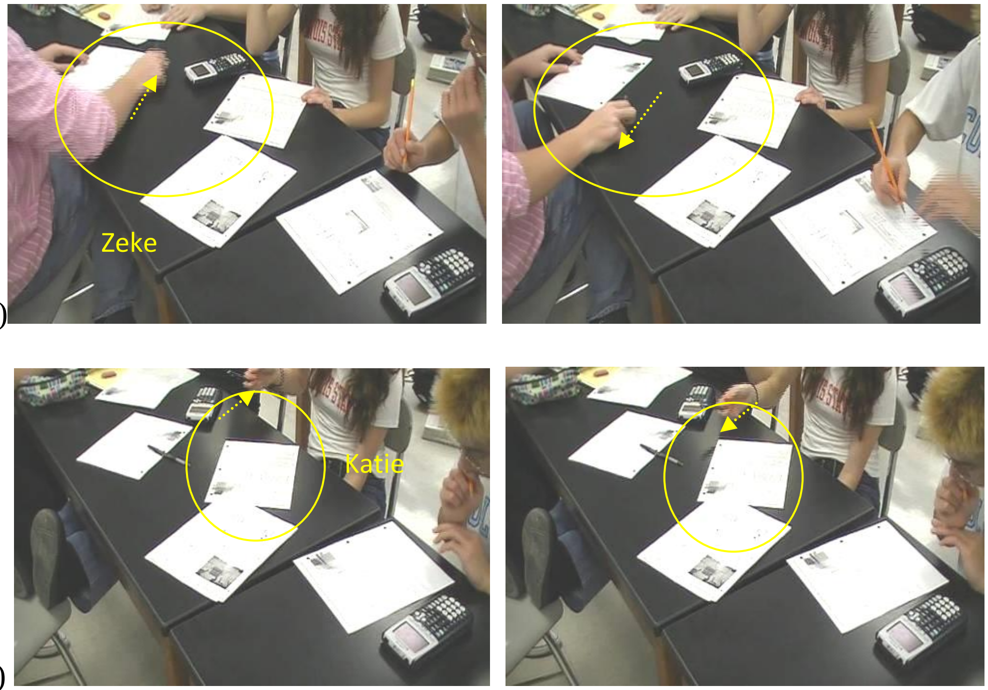
Figure 4.1.12. (Day 7). Textbook page on transverse and longitudinal waves (Hsu, 2004, p. 267).



(a)

(b)

Figure 4.1.13. (a), (Day 7, 39:23). Zeke attempts to explain his interpretation to his peers by pretending to create a wave in the slinky by moving his hand forwards (picture to the left) and backwards (picture to the right), instead of side to side. (b), (Day 7, 42:00). Katie pushes forward with her hand as she speaks as she engages with the meaning of “distance between successive compressions.”

His group peers later enacted this same gesture. They were working on the following practice problem: “A longitudinal wave that has a frequency of 20 Hz travels along a slinky. If the distance between successive compressions is 2 ft., what is the speed of the wave?” Katie and Addy both made the same UHG that Zeke first used earlier as he made meaning of the “distance between successive compressions” in the problem. Katie’s gestures, seen in Figure 4.1.13b, occurred while she verbally interpreted the written text–, “so it’d be like that, it’s going like this [same forward-and-backward hand gesture] instead of like that [side-to-side hand gesture], so I think it would be the wavelength.” She described the orientation of the hand’s back-and-forth motion as she contrasted the forward-and-backward motion in this context with the side-to-side motion that may have been more familiar from past experiences. The gesture made her contrast salient and allowed her to publically reason that the compression was simply this forward-backward gesture that created the wave pulse, which was similar to the side-to-side gesture used to create pulses in previous activities. By defining *compression* in this way, she further reasoned that the “distance between successive compressions” stated in the text must be the distance between wave pulses, which led her to the conclusion that this must be referring to wavelength.

Kevin also used the BFG to add meaning to his understanding when he later realized that “compressions are like the uh top parts of the longitudinal ones,” which he said as he simultaneously gestured the top peak of a sinusoidal UHG. Together, these provide evidence of his linking a transverse or sinusoidal wave using both speech and gesture) to longitudinal waves using only speech. Through his speech and gesture, he publically connected a transverse wave’s sinusoidal form and UHG with a longitudinal wave’s compressional form and BFG. It is not just the gesture that promoted this connection, but the equivalence of the specific part of the sinusoidal UHG to the new idea of compressions in longitudinal waves. He connected these compressions with the top part or crest of the sinusoidal UHG, making the UHG critical to his development of this idea and his articulation of the idea to his peers.

Zeke again used the BFG as he publically described what wave characteristics he considered as directly controlled by the source. The gesture was an enactment of the wave source for the slinky and afforded Zeke a referent for his idea. Zeke suggested “wave height,” then made a wide, sweeping UHG seen in Figure 4.1.14a-b as he said, “you can make it HIGHER” emphasizing the word *higher* by drawing out his speech as he simultaneously gestured. Across speech and gesture, Zeke demonstrated conceptual understanding, as well as how to manipulate artifacts as he referenced wave-generation in slinkies with his hand’s BFG. By using the term *height* instead of *amplitude*, which is the scientific term that the students had not been introduced yet, Zeke demonstrated meaningful and scientifically canonical understanding.

Figure 4.1.14. (Day 8, 28:35). Zeke suggests “wave height” as he makes a wide, sweeping BFG.

Megan also used the BFG by moving her hand back and forth quickly while suggesting frequency as a wave characteristic whose value is directly controlled by the wave’s source. Zeke and Megan’s respective use of the BFG suggested that their ideas were stemming from their experiences in the slinky experiments. The BFG mediated between the question of what wave characteristics were controlled by the source and the back and forth motion used to create waves in a slinky. Their prior understandings related to waves, which were based on their experiences creating waves with the slinky, facilitated their conceptual understanding that a wave’s amplitude depends on the source's amplitude. Moreover, they offered the other students an opportunity to think about how the hand had direct control over both wave characteristics, frequency (i.e., how quickly the hand moves back-and-forth) and amplitude (i.e., how far the hand moves back and forth).

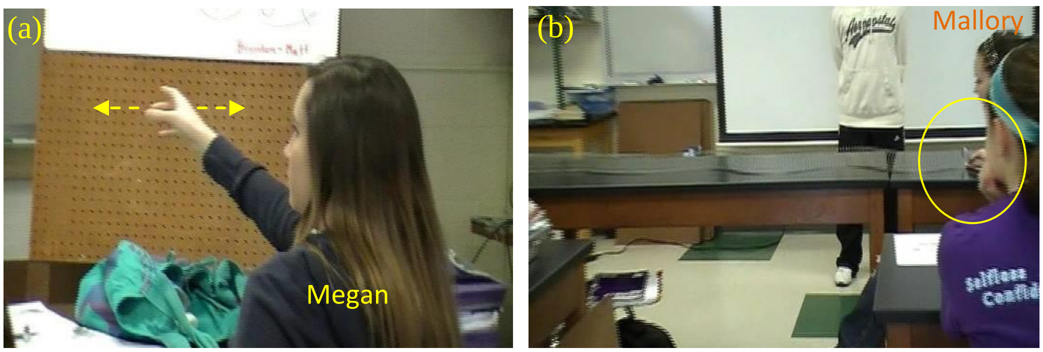


Figure 4.1.15. (a), (Day 8, 40:29). Megan gestures right and left to represent the side-to-side motion of a particle in the medium of a wave. (b), (Day 8, 41:04). Mallory creates waves in a slinky to clarify the "right" and "left" directions.

Later in the same discussion, Megan again used the BFG with her speech. I asked the class, "how does the particle or piece of the material compare to the motion of the pulse?" Megan responded saying, "I think when the pulse travels through, it moves to the right [gestures her hand to the right, as seen in Figure 4.1.15a] with the pulse and then it moves back to the left with the pulse [moves her hand to the left]." To clarify the "left" and "right" aspects of Megan's claim, I had Mallory create a wave on a slinky in front of the class. I asked everyone to look at her hand's motion and compare its side-to-side motion to the pulse's forward motion down the slinky seen in Figure 4.1.15b. In doing so, I revoiced Megan’s speech and gesture, but included the actual artifacts she appeared to envisage during her utterance. This alleviated the need for students to imagine the motion of the hand and slinky since it was now there in front of them, and allowed me to focus the students’ attention to explicit aspects (i.e., the hand’s side-to-side motion and the pulse’s propagation along the slinky).

Two days later, on Day 10 (see Appendix), Zeke called upon the UHG in the same way it was first used on Day 1 to enact water waves, but here, Zeke used it to show the propagational motion of a wave in a standing wave, as seen in the photograph in Figure 4.1.16. Zeke made an UHG with one hand while simultaneously using the other to depict a central axis. The lateral movement of his hand represented the propagation of the wave as it crossed the central axis, articulating his point about how the intersection created a node. The lines drawn over the photo are based on the motion of Zeke’s hand and his verbal narration of his gestures. The discourse excerpt shown in Figure 4.1.16 shows that Zeke envisaged the standing wave as a moving wave on a string, whose reflections aligned with the incident waves such that the points on the middle axis where both the incident and reflected waves cross and, therefore, appear as stationary nodes. Although Zeke’s speech did not have this level of articulation, the underlying concepts were the same, and his speech together with his gesturing revealed his scientifically accurate thinking. However, his interpretation was likely not perceived by students in the same way that I did at this moment in class. Since I already understood how standing waves are created and could see his gestures and speech working together to express his conception, it was easier for me to understand his thinking. His ideas were not taken up by his peers, possibly due to a variety of factors, including difficulty in following his thinking, lack of attention, or inability to see his gestures.

All transcripts in this manuscript will follow the same coding scheme. Speech will be written as text, and researcher comments will be text that is both italicized and placed within brackets. Overlapping speech will be bounded by an equal sign at the beginning and end of both overlapping utterances. A long dash will denote when a participant is interrupted.

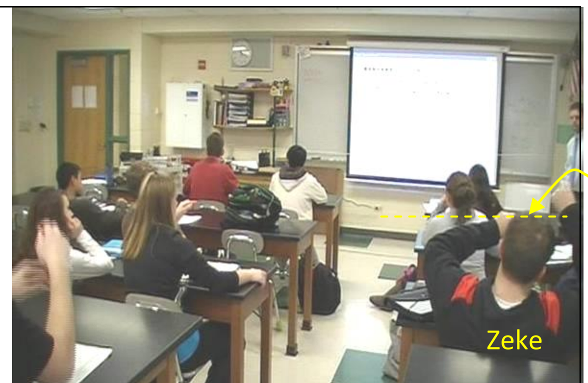
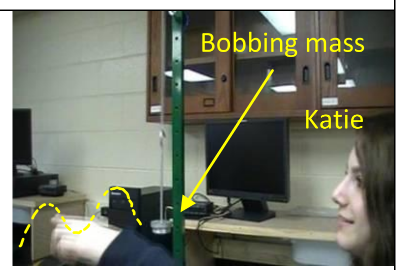
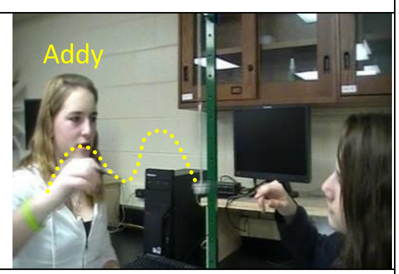
1	Teacher:	Do you see the stationary points in the standing wave, how can we explain those?	 [*Zeke's UHG with his right hand enacts a wave in a standing wave as his left hand represents a central axis.*]
2	Zeke:	because if like the wave is going like up here [*not pictured, but right hand moves to right representing incident wave*], then well, this is the point where it's in the middle [*uses left hand to mark the middle axis which is shown to the right as a dotted line*], then when it's coming back it would be going up and then coming back through the same point [*right hand traces the path of a reflected wave moving left to the middle axis shown to the right as a solid line*].	

Figure 4.1.16. (Day 10, 5:25-5:54). Zeke's explanation for the existence of nodes in a standing wave.

The last day of the unit (Day 12) was a lab practicum over the entire unit. A mass hanger with one 100-gram mass hung from a vertical spring and bobbed up and down. The students were asked to consider this mass hanger as a potential wave source, and to measure in their teams all possible characteristics of waves that would have been generated if a medium were attached to the bobbing mass. However, since there was no medium attached, the bobbing mass was not generating any visible waves like the waves in a slinky. Students' team exploration of the bobbing mass was done in preparation for an oral examination in which I would ask different questions to the members of a team, which would be answered individually. The students did not know the questions before they were asked. The students could measure the period, frequency, and amplitude of waves generated by the bobbing mass, but they were not offered these possibilities. They had to determine what characteristics they could measure, how to measure each of them, and actually make the measurement in preparation of the oral exam. This was challenging since the waves propagating away from the wave source (i.e., the bobbing mass) would be in air, and, thus, not visible to students. This also limited the wave characteristics students could measure since wavelength and propagational speed would be not possible for students to measure in this context.

The transcript shown in Figure 4.1.17 captured the first minute of the focal group preparation before the oral evaluation that Kevin videotaped. Both the BFG and UHG were present. Katie and Addy used the UHG to first indicate the wave's propagation direction that was not visible. Katie enacted the wave by using an UHG to trace its sinusoidal shape as it propagated through the air, thus visualizing it for both herself and her teammates (Fig. 4.1.17, Unit 2). Such visualization was necessary for the measurements that students would be asked about during their subsequent oral examination. Katie's and Addy's UHGs can be seen in Units 2, 5, and 7. In each of these cases, the mass's bobbing motion was aligned with their hand's up-and-down motion, as the hand traced a sinusoidal path of propagation through the air away from the bobbing mass. These gestures alluded to the back-and-forth motion associated with waves, the sinusoidal shape the students were familiar with, and the waveform graph from which they knew how to make measurements. Thus, their UHG acted as a bridge between their conceptions of wave characteristics in familiar contexts (i.e., waves produced in a slinky) and in various modalities (i.e., waveform graphs) and the new unfamiliar artifacts (i.e., mass on a spring) within a context with which they had not directly worked (i.e., bobbing mass).

1	Addy:	Alright, well like how do we like measure period and stuff if there's no waves? [*Addy puts the mass into a bobbing motion by pulling down on it*]	
2	Katie:	Well, because it's going up and down, and if you attach something here [*points to the bobbing mass, and her hand bobs up and down with the mass*] it'd be going like that [*see picture, her speech pauses as she traces the dotted sinusoidal line path shown in the figure. Her hand's up-and-down motion is synchronized with the bobbing motion of the mass on a spring*] and this the source [*points to the bobbing mass*]	
3	Addy:	So we can't like measure anything though, right?	
4	Katie:	Yeah you can	
5	Addy:	You can get the period [*see picture, as she speaks she moves her hand tracing out the dotted sinusoidal line shown in the figure. Her hand's up-and-down motion is synchronized with the bobbing motion of the mass on a spring.*]	
6	Katie:	You can get the period as the time it takes to go one	
7	Addy:	Cuz we can't like see a wave [*see picture, her flat palmed hand gesture traces out the dotted sinusoidal line shown in the figure*] so how do we know, how can we time it to get from like point A to point B?	
8	Kevin:	Well,= ya know we can= calculate the amount of time it takes to go back and forth so we can get the frequency	
9	Katie:	=Can't we get distance?= [*overlaps with Kevin's speech*]	

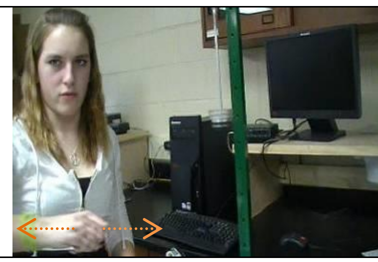
10	Addy:	Is this the wave, cuz it's like a slinky? [*gestures to the compressions in the spring using her index finger and thumb*]	
11	Kevin:	Like a compression, or like a longitudinal wave?	
12	Addy:	Yeah, was the longitudinal like the one where you push it this way? [*makes a forward-and-backward pushing gesture that is not visibly clear enough for a digital still photo*]	
13	Kevin:	Yeah and then the slinky like spirals like going forward	
14	Addy:	And this one was transverse, going back and forth [*makes the side-to-side BFG as if creating a transverse wave seen in the picture to the right. The dotted arrows depict the side-to-side motion of her hand.*]	
15	Kevin:	Yeah the one where it just waves	
16	Addy:	Fine	

Figure 4.1.17. Transcript of segment during the focal group's lab practicum on the last day of the instructional unit.

The similarity in appearance between the spring in the spring-mass system in this activity and the slinky that students had used in past activities generated confusion as seen in Unit 10 (Fig. 4.1.17). Addy saw the spring compressing and stretching as the mass bobbed and mistakenly connected it to the compressing and stretching of a slinky as longitudinal waves pass through it. Her focus was on the spring, and its stretching and compressing as the medium, instead of the bob as a wave source in the medium of air, and its back and forth motion that produced transverse waves in the air around it. She and Kevin, used gestures as they talked (although Kevin's gestures cannot be seen easily as he was holding the camera) to negotiate longitudinal (Unit 12) and transverse (Unit 14) waves in relation to the vertical spring in front of them. Their iconic gestures depicted how their hand's motion had created waves in their previous experiences with slinkies, with which they were more familiar than the bobbing mass, and provided an anchor to which they could link the bobbing mass. They were considering here for the first time the wave nature of the mass-spring system, so the resemblance between the spring and the slinkies, with which they were most familiar, caused them to incorrectly associate the two objects that were not functionally equivalent. The slinky had been the wave's medium, with their hand acting as its source. The spring in this context had no relevance to the waves they were to analyze, except to provide the driving force to maintain the bob's up and down motion. This was a critical distinction between this context and the previous slinky contexts; the spring was not the wave's *medium* as in the slinky, but instead, it was part of the spring-mass system that acted as a wave *source*, which exhibited wave characteristics that I intended them to measure. Kevin referred to the slinky spirals going forward (Unit 13), when longitudinal waves were made in the slinky, which alludes to the concept of wave propagation, albeit incorrectly regarding this particular task. His observation stemmed from their iconic BFGs that provided a scaffold to their consideration of the perspective of the back and forth motion, which promoted their examination of the medium in which the wave propagates. Defining the medium as the spring would imply that they were analyzing longitudinal waves in the spring, whereas if air were the medium, the waves produced must be transverse. The gestures enacted their thinking about the bobbing mass in relation to waves it might produce by utilizing the BFG as a wave source. This allowed them to link what they already understood about waves from their prior experiences with the BFG to the bobbing mass since both are wave sources. The BFG was not only more familiar, but was also often used with a slinky–a medium in which the propagation of waves produced by the BFG was visible. In the case of the bobbing mass, the medium in which the wave propagation was taking place was being negotiated by the group and could be either the air or the spring attached to the bob. The choice of medium depended on the orientation of the bob's back and forth motion with respect to the line of propagation, which defines the wave as longitudinal or transverse. In Unit 5, Addy used the UHG to enact the propagation of a transverse wave in the air that would otherwise be invisible. The linkage between their BFG and the bobbing mass helped visualize the waves the bobbing mass would produce in the spring or the air, which were invisible in both cases, and choose which type of wave (longitudinal or transverse) to consider for their analysis.

Summary

The sinusoidal UHG emerged spontaneously on the first day of the unit and I became aware of its prominence as I observed my students' repeated use during this first lesson. In light of this, I realized gesturing would be a critical modality for my students' conceptual development and engagement in my classroom. Thus, I incorporated both types of gestures (UHG and BFG) into many of the activities throughout the rest of the unit to promote their usage and development, in hopes that gesturing would become a cornerstone for meaning making around wave characteristics across the entire unit. Both UHG and BFG were embodiments of micro-level motion associated with waves (Wittmann, 2002), which captured, respectively, the back-and-forth motion of a wave source and of the particles in a medium through which the wave passes. These hand gestures served as teaching and learning tools as I helped students construct meaning of wave characteristics such as amplitude, period, and frequency, as well as the sinusoidal propagation of waves. I used the BFG as a multimodal scaffold for students to extrapolate a wave's period and amplitude from a wave-form graph. I repeated Mallory's BFG in front of the class to assign it additional value, and used deictic gestures to explicitly link the motion of her gesture to the points on a publically-displayed waveform graph that she described from her seat. I also used the BFG in conjunction with other modes to help students connect actions and experiences in their slinky experiments with diagrams and graphs of waves. I often superimposed both my UHG and BFG over diagrams and graphs in front of students to help them make these connections. I superimposed my UHG over the wavy-line drawing to suggest that the UHG was an enactment of the underlying motion associated with the wavy-line diagram. I revoiced Oliver's idea and incorporated the BFG by patting the screen in-and-out at the center of a ripple drawing to provide perspective to the diagram. I also superimposed a BFG/UHG combination over top of the y-axis of a waveform graph to link a motion sensor's sinusoidal graph to the student's hand as it created waves in a slinky.

Gesturing shared resemblance with other modalities. The sinusoidal UHG embodied students' drawing of a wave on Day 1, and developed over time particularly as students engaged with the sinusoidal shape of waveform graphs. By the last two days of the unit (Days 11 and 12), students called upon UHGs to envisage wave propagation abstractly for standing waves and the mass on a spring's wave produced in air, neither of which allow for propagation to be directly observed.

The BFG stemmed from students' experience producing waves in a slinky during their experiments as a prominent means for communicating about a wave's source, and the oscillatory nature of wave sources in particular, especially when the wave source is one's hand holding a slinky. It helped to articulate points of view or perspectives in our diagrams of experimental setups, and acted as a scaffold for students to understand how a wave's period and amplitude were depicted on a waveform graph. As students used the BFG in relation to graphs, which had a sinusoidal shape, the BFG acquired an undulating characteristic as students shifted from simply shaking their fist back and forth to tracing, in air, the sinusoidal shape of graph's curve. This combination of the BFG with the UHG mediated students' linking the wavy nature of the graph depicting wave propagation (in UHG) with the back and forth motion of the wave source and the medium's particles (in BFG). In this way, the UHG came to represent the back and forth motion of the medium as waves propagated through it (particle motion). Therefore, both gestures were integral to my students' concept development of wave characteristics, especially those characteristics such as amplitude and period whose values depended on the wave source's back-and-forth movement.

Both gestures scaffolded my students toward more advanced discussions and meaning making as they continued to call upon the gestures throughout the unit. The gestures mediated students' thinking about wave characteristics that were controlled by a wave's source and their experiences producing waves in a slinky. They also helped the focal group during the lab practicum when the students were confused as to how the wave was propagating. Katie's iconic gesturing depicted the wave's propagation, as well as its undulation, by tracing the sinusoidal shape she imagined and shared with her team.

As gestures evolved in both form and function throughout the unit, so did students' conceptual understanding. For example, Brian successfully extended the representation of the concepts of wave cycle and wave period from one modality to another, namely from gesturing and using artifacts to graphs. Moreover, by shifting to the graphical modality in which he had not yet worked, he was able to use the time axis, afforded only by the graphical modality, alongside his understanding of how one wave cycle is represented on a graph to quantify the wave period, or duration of one wave. As another example, Zeke was able to appropriate the textbook's explanation using a BFG and use it in his explanation of the term to his peers in relation to their shared experiences. Katie also used a BFG in a similar way to reason that a compression is created by a forward-backward gesture, which is analogous to the side-to-side gesture that was used to create pulses in previous activities. By defining *compression* in this way, she further reasoned that the "distance between successive compressions" must be the distance between wave pulses, and must be referred to as the wavelength. Kevin also used the BFG to connect the crest of a transverse wave with the compression of a longitudinal wave. Thus, gestures were a critical modality for both my students and myself, as their teacher, to call upon while interacting and making meaning with each other. The intertwining of gestures with other modalities is further explored and discussed in the sections 5.1 and 5.2.

Diagrams

In this section, I present how the form and function of diagrams evolved in my class during the 12-day unit on waves. Gesturing, on which Section 4.1 focused, in addition to other modalities, will be also discussed as it relates to the ways in which my students and I made meaning of diagrams and wave concepts.

Diagramming and Its Co-Construction Among Classroom Participants

On the first day of the unit (see Instructional Outline in Appendix), I asked each student to draw a wave on a small 1 x 1 ft. whiteboard. They then stood in a circle as a gallery-view of one another's whiteboards and unveiled their boards simultaneously by flipping them over. To initiate a discussion over similarities and differences in their diagrams, I displayed my board showing a wavy-line drawing, which I had anticipated as being similar to many student drawings (Fig. 4.2.1). During the brief whole-class discussion that followed, students noticed two other prominent diagrams, all three of which are shown in Fig. 4.2.1. The wavy line is on the left, a partial ripple diagram commonly seen as depicting volume controls on electronic devices is shown in the middle, and a complete two-dimensional ripple diagram similar to an above view of ripples in a calm body of water is displayed on the right.

These three diagrams were the focus of the subsequent discussion that generated more ideas about waves including how they could all depict waves from different perspectives, and how all waves share an undulating, or back-and-forth characteristic. As discussed in detail in the section 4.1 on gestures, students used undulating hand gestures to attribute up-and-down motion to the wavy line diagram, as well as forward propagation as the undulating hand was moved forward. The ripple diagrams were discussed as an "above view" of a wave, which two different students suggested as they explained to the class how the wavy line and ripples were both depicting a wave, but in different ways. As one of these students, Oliver had described, the ripples were an “above view,” and the wavy line was a “side view” of a wave. These two wave diagrams and the wavy line in particular, would become part of my classroom’s cultural tools and serve as standards for how to diagram waves that would be composed and read throughout the instructional unit. By calling considerable attention to my students’ diagrams during the first day, and positioning them as objects of discussion, I highlighted diagramming as a cultural practice and valuable modality for making meaning of waves, which allowed my students to express, negotiate, and develop their ideas throughout the unit.

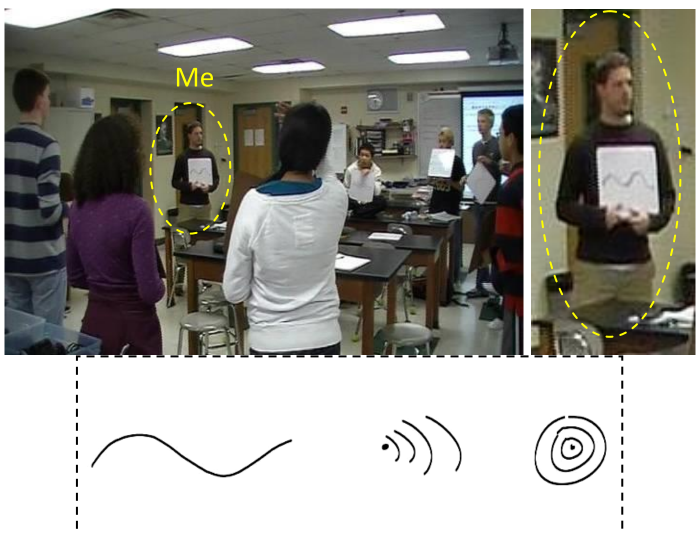


Figure 4.2.1. (Day 1, 9:17). Gallery-view of students’ and my wave diagrams during the 1st lesson of the unit, with the three most common student-suggested wave diagrams sketched underneath.

In my class, diagrams were particularly useful for representing spatial layouts and the relative positions of people and artifacts during an experiment. Although my students had been consistently conducting experiments throughout the year, diagramming experimental setups had not been an explicit focus. I had not explicitly prompted students to draw such diagrams as part of conducting experiments. Students had the choice to diagram their experimental setup alongside their results, which they were to always present on a 2x3 foot whiteboard following data collection as part of any experiment. I often modeled how to diagram experimental setups, as well as led whole-class discussions about them, to encourage students' initiative to diagram as a legitimate and valuable classroom practice, but students were never explicitly asked to include a diagram of the experimental setup on their whiteboards as part of their results summary.

For the first experiment of the wave unit (Day 2), similarly to all previous experiments, there were no student handouts. The student inquiry was driven by a purpose statement projected on the screen in front of the class that stated, "Graphically and mathematically represent the relationship between wave speed and wave height for a long metal slinky." The student groups collected data and each summarized their results on a 2 x 3-ft whiteboard. After the experiment, I selected four groups' whiteboards to display publically as objects for a follow-up class discussion (see Figures 4.2.2a-d). Only two of the four groups had drawn diagrams, which are denoted by the dotted circles in the figure. Although the displayed boards represent only four of the seven groups, they captured both the type and ratio of diagrams drawn. The presence of diagrams, without any prompting, on about half of the groups' whiteboards demonstrated that diagramming was useful and valued modality for some students. The lack of detail in their diagrams (such as labels, including brackets and arrows) as compared to the diagrams that students would eventually draw later in the unit (e.g., see 4.2.14), suggested that early on into the unit, students were not proficient in *how* to use diagrams as a cultural tool.

The focal group's diagram (Fig. 4.2.2a) had the most detail and showed the slinky being held by a person at each of its ends. Its only purpose was to show the positions of the participants relative to the slinky (an experimental artifact). The other diagram seen in Fig. 4.2.2b does not show any participants and their positions. Its function was likely to show the *shape* of the slinky at some instant as waves traveled through it. In doing so, students were most likely calling upon the wavy-line diagram from the previous day. The text listed next to the diagram, "overhead view of motion," supported this connection since the discussion of the wavy line diagram during the previous day emphasized perspective or vantage point. The wavy line that had been perceived as a "side view" of a wave during the previous day's discussion was now correctly described by these students as an "overhead" or above view. This suggested that the students were not stating verbatim the perspective from the previous discussion, and indeed understood how to assign perspective that varied for the wavy line between this instance and that of the previous day. The wavy or sinusoidal shape of the slinky as waves traveled through it in this experiment resembled the wavy line drawing, and might have motivated the students in this group to include it as a diagram. The choice some students made to include the wavy line diagram on their whiteboard for this experiment indicates some value that these students had placed on this form of diagram, and that they had constructed this representation as a meaningful depiction of a wave. The public nature of both diagrams promoted diagramming as a practice of communicating in my classroom, and as a prominent modality for students and myself to call upon as we continued to make meaning of waves.

During the next day's (Day 3) follow-up lecture, I modeled for students how to diagram the experimental setup from the previous day's experiment. Using speech and gestures, I focused the class' attention to my diagram's features such as the labeled arrows that represented measured quantities, and the positions and actions of students relative to the experimental artifacts (see Fig. 4.2.3). My intention was to help my students appropriate diagramming practices and enact them during future diagramming opportunities. I considered the syntax and semantics of diagrams (i.e., the *diagrammatical grammar*) as a resource of the sociocultural practice of science that could facilitate the collective construction of ideas.

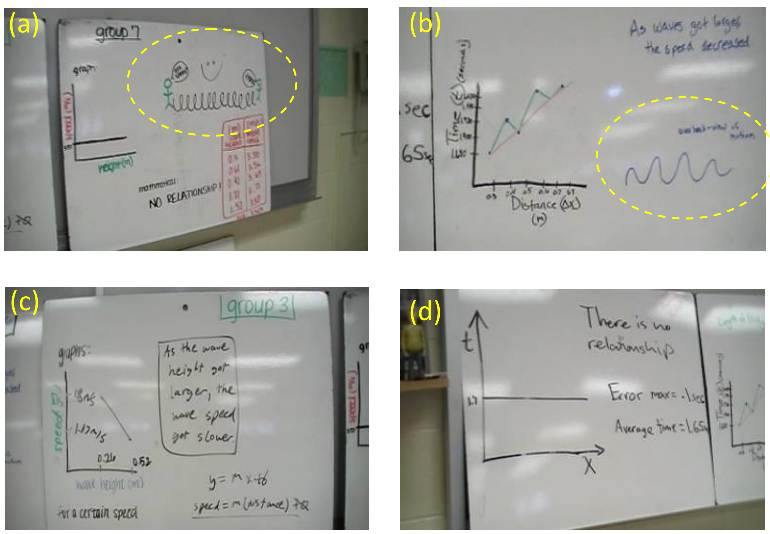


Figure 4.2.2. (end of Day 2). Student-groups' whiteboards of wave speed vs. height slinky experiment. (a) shows the focal group's board.

The following day (Day 4), when Raymond suggested an experimental setup that utilized a motion sensor to measure the quickness of a person's hand that generated a wave in the slinky, I asked him to diagram the setup in front of the class, which is where the transcript in Figure 4.2.4 begins. In Unit 1, I asked Raymond to describe where he envisioned the motion sensor to be located. He immediately elected to diagram the location of the motion sensor as he also spoke.

By publically diagramming the setup, the position of the motion sensor relative to the slinky and hand's motion became well defined for the entire class. Raymond first depicted someone's hand holding the slinky at the bottom, and then drew a motion sensor facing the hand along the axis of its side-to-side motion. He then went on to label the diagram using arrows labeled "+" and "-" such that moving away from the sensor resulted in motion in the positive direction and motion toward to sensor was therefore in the negative direction, as seen in Unit 3. His speech in conjunction with his diagramming allowed Raymond to articulate his ideas for the rest of the class providing an appropriate setup given this experiment's purpose. This also provided me access into Raymond's understanding at that moment, of the motion sensor's utility and function as a data collection device. It also suggested that he understood the spatial arrangement of the motion sensor in relation to the artifacts (hand and slinky) and the manipulation of the artifacts (the hand's moving the slinky back and forth).

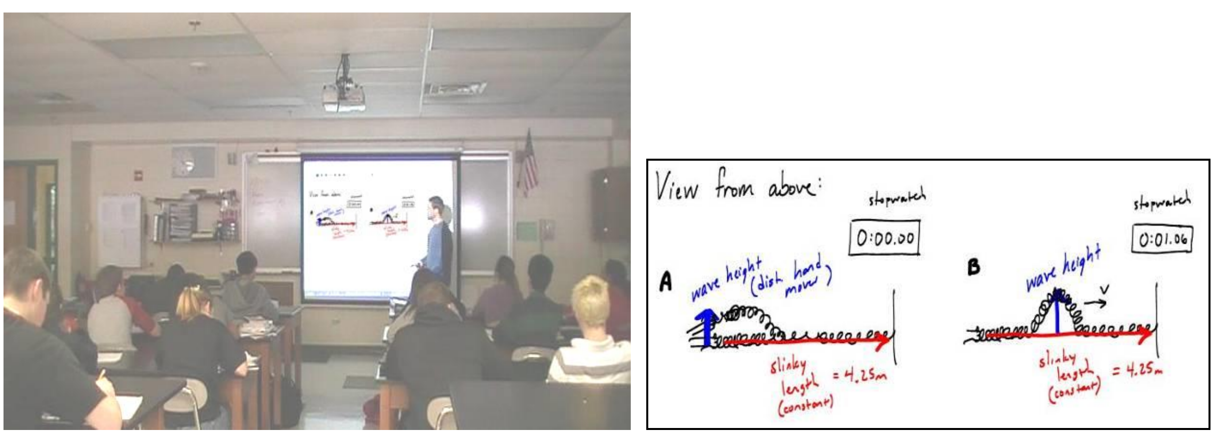


Figure 4.2.3. (Day 3, 4:00). During the post-experiment lecture, I draw and explain my diagram of the experimental setup for the wave speed vs. height slinky experiment.

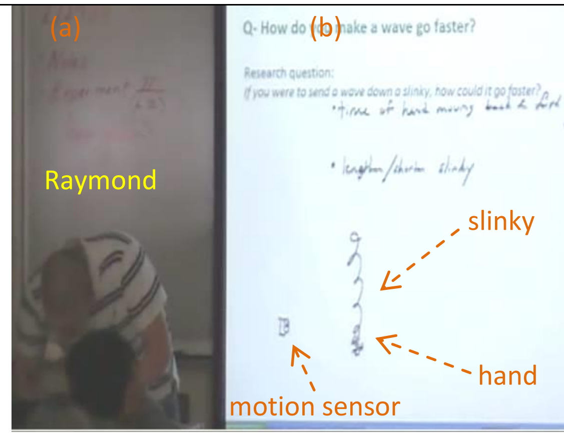
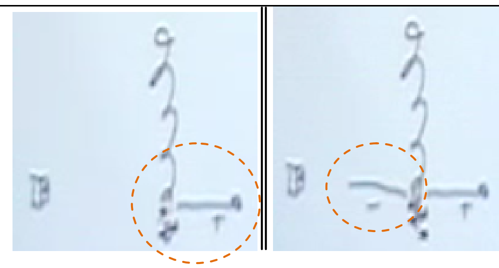
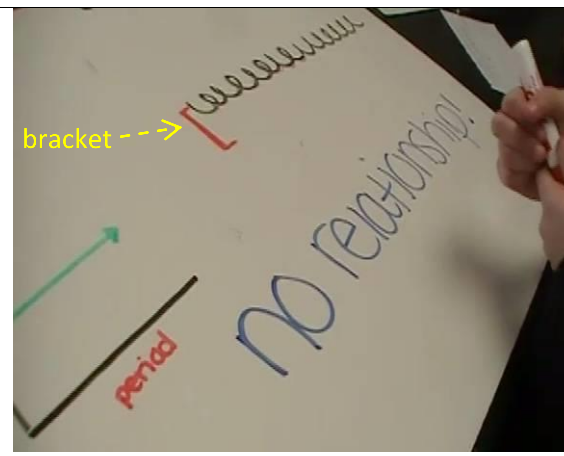
<table>
<tr><td>1</td><td>Teacher</td><td>Describe where you’re putting the motion sensor so we know what’s going on.</td><td rowspan="2">
</td></tr>
<tr><td>2</td><td>Raymond</td><td>Oh ok. So you have your slinky going like this [draws a slinky]
and you have your motion sensor [pauses his speech as he draws a motion sensor]
here, and then your hand [Raymond attempts to draw a hand holding the slinky at its bottom and Raymond and the class laughs because his drawing does not look much like a hand]</td></tr>
<tr><td>3</td><td>Raymond</td><td>And then as it moves this way it’s positive [draws an arrow pointing away from the slinky and labels it as “+” as seen in picture (a) to the right]
and as it move this way it’s negative [draws a line pointing towards the slinky and labels it as “-” as seen in picture (b) to the right]</td><td></td></tr>
</table>

Figure 4.2.4. (Day 3, 23:53-24:36). Multimodal transcript of Raymond’s presentation to the class of an experimental setup to obtain the relationship between wave speed and hand quickness [or period].

On Day 4, while the focal group was working on experimentally determining the relationship between wave speed and hand-quickness (or period), Katie suggested they diagram their setup when they were summarizing their findings on a large 2 x 3-ft. whiteboard. Figure 4.2.5 shows the excerpt of the multimodal discourse during the collective diagramming. The final diagram of the setup seen at the end of the transcript (Unit 13) resembles Raymond’s diagram of the setup during Day 2’s whole-class discussion (Image (b), Unit 3, Fig. 4.2.4). In both cases, the diagrams showed a static slinky, since there were no waves drawn into the slinky, and a motion sensor to the side of one of the slinky's ends. Katie also elected to draw a stopwatch to denote how they measured time. Their choices in what objects to draw reflected a collective understanding of the relevant artifacts for the experiment including those objects that were being manipulated (e.g., slinky) or used to collect data (e.g., motion sensor and stopwatch), and their spatial positions relative to each other.

<table>
<tr><td>1</td><td>Katie</td><td>We can draw our setup.</td><td rowspan="4">
</td></tr>
<tr><td>2</td><td>Addy</td><td>=Yeah=</td></tr>
<tr><td>3</td><td>Kevin</td><td>=Yeah= that's good.</td></tr>
<tr><td>4</td><td>Katie</td><td>Ok we need a slinky [draws a slinky].
Ok, and then, [draws a bracket at one end of the slinky as pictured to the right]
that would be the period, right?</td></tr>
<tr><td>5</td><td>Addy</td><td>Yes, cuz that's like I move my hand from like here [points finger to the top and bottom of the bracket]
and then I moved it like—</td><td rowspan="4">
Bracket is now labeled "t/period".</td></tr>
<tr><td>6</td><td>Kevin</td><td>—It can be the time slash amplitude.</td></tr>
<tr><td>7</td><td>Addy</td><td>Time slash period [speaks what Katie writes. Katie then labels the bracket "t/period" in the picture to the right].</td></tr>
<tr><td>8</td><td>Kevin</td><td>I think we should draw like arrows for it cuz then it shows that it's going this way [down] and then it comes back [up] [Katie draws a double-headed arrow as seen in the picture to the right].</td></tr>
</table>

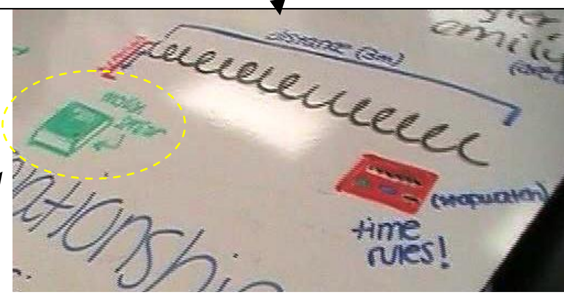
9	Addy	Um, we can show our distance. [*Katie draws a bracket along the entire slinky and labels it "distance (3m)"*] Good! [*Katie draws a stopwatch*] And then we had a motion sensor right here, right? [*Addy points to the end of the slinky where the brackets are*]	*Bracket depicting "distance"*
10	Katie	Yes.	
11	Addy	Kevin, can you take this [camera], it's kinda hard to draw and hold.	
12	Kevin	All right (*says laughing*).	
13	Addy	So it should be facing this [end of the slinky]. [*draws a motion sensor and labels it "motion sensor" denoted by the dotted circle in the picture to the right*]	

Figure 4.2.5. (Day 4, 26:30-29:48). Multimodal transcript of focal group diagramming their experimental setup for the wave speed vs. hand-quickness (or period) slinky experiment.

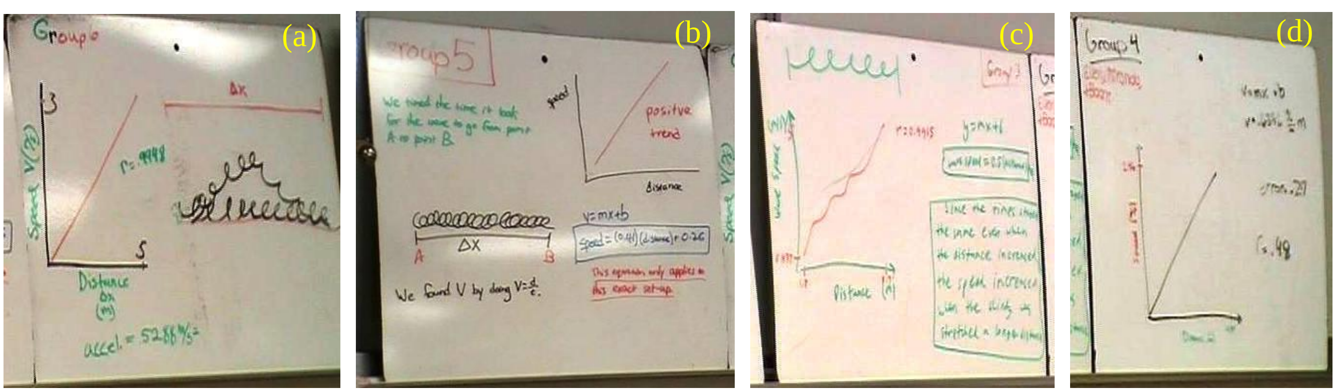


Figure 4.2.6. (Day 4, 34:30). Student-groups' whiteboards for the wave speed vs. slinky length experiment. (b) Text accompanying the diagram: "We timed the time it took for the wave to go from point A to point B."

The focal group was one of three groups conducting an experiment to find the relationship between wave speed and period. The other four groups were conducting an experiment seeking the relationship between wave speed and the slinky's length. The four groups' whiteboards summarizing their experimental results are shown in Fig. 4.2.6. I had not explicitly asked students to draw diagrams as part of their preparing a whiteboard, and of these four groups only two (4.2.6a, b) chose to include one. The resulting whiteboards of the three groups who conducted the other experiment are shown in Fig. 4.2.7. Of these three groups, only the focal group (Fig. 4.2.7a) chose to diagram their experimental setup.

All three of the diagrams that students had created (Figures 4.2.6a,b and 4.2.7a) shared several similar characteristics. They each depicted artifacts–objects and devices utilized or manipulated in the experiment such as the slinky, and they all made use of labeled brackets. As previously discussed, these brackets represented an interval between two points. In modeling how to diagram various experimental setups throughout the year, I repeatedly drew labeled arrows, but never brackets, suggesting that the idea of using brackets to represent intervals emerged spontaneously from among the students. The growing predominance of brackets as a symbol suggests that students were both discursively shaping this symbol's referent (e.g., the distance or interval), and using it to communicate their thinking. The growing utilization of brackets to diagrammatically represent an interval of distance or time functioned as a scaffold for students and me to communicate about an experimental setup. Since all three groups who included brackets were not prompted, this provides evidence of a shared understanding among students about the diagrammatical representation of an interval, since I had consistently used arrows, and not brackets, throughout the school year as a symbol I had consistently suggested to represent intervals including distances. It is evident that students associated arrows with direction, as seen with the arrows the focal group used in their diagram depicting their hand's movement back-and-forth. However, in most cases, brackets were use to indicate distance between two points.

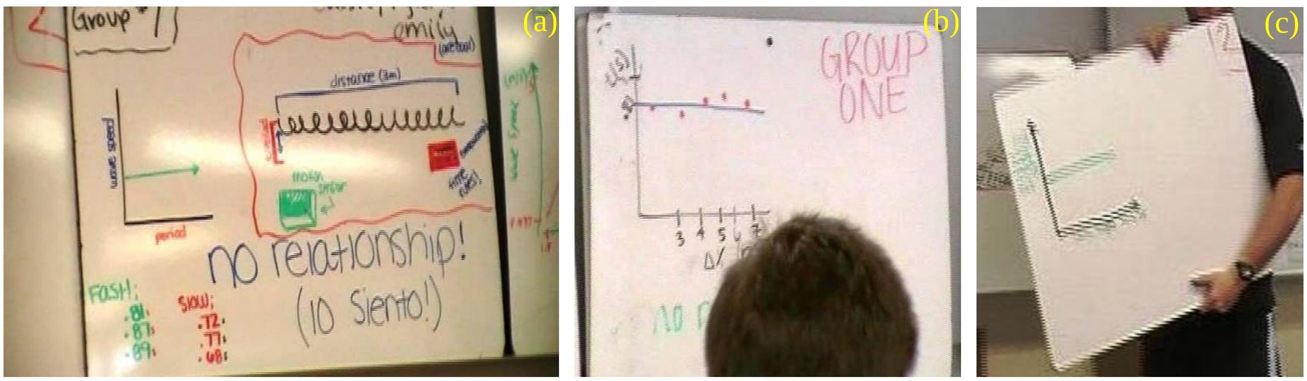


Figure 4.2.7. (Day 4, 41:12). Student-groups' whiteboards for the wave speed vs. period experiment. (a) Focal group's board.

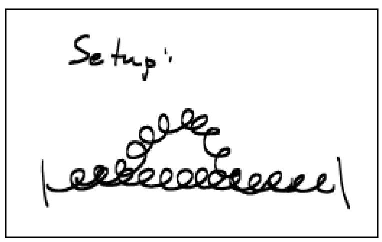
The focal group's whiteboard seen in Fig. 4.2.6a on Day 4 shared a similar trait with the diagram of the first slinky experimental setup I drew for the students during Day 2's class (see Fig. 4.2.3). In both of these diagrams, the students' manipulation of the slinky during the experiment was diagrammed using a superposition of the instance *before* the manipulation when the slinky laid in a straight line and *after* the manipulation as a wave propagated through it. However, the group did not attempt to represent the propagational aspect of this wave in the way I had modeled with an arrow labeled *v* (velocity) in the direction in which the pulse traveled.

None of the groups diagrammed velocity in this way, but the group whose board is shown in Fig. 4.2.6b wrote text as a caption below their diagram in which they indicated that they had determined velocity as well as how they had done this. “We found V by doing $V = \frac{d}{t}$.” They also used captions for their diagram to explain how they measured their distances and times used in the calculation of velocity. Although brackets in general do not have any directional aspects, this group labeled the sides of their bracket as “A” and “B,” and utilized this feature to add both the directional and propagational aspects using the supporting text, “We timed the time it took for the wave to go from point A to point B.” The order of these letters also suggested directionality for the distance of its linear motion (propagation).

The three groups who diagrammed (Fig. 4.2.6a, b & 4.2.7a) all included text as captions or labels in their diagrams, which suggested that students in these groups viewed these characteristics as helpful to their articulation of other diagrammatical features. Written text is a mode that can act in isolation from other modes, but in these cases was treated as a diagrammatic characteristic that added meaning to other characteristics, such as linking a term (e.g., “distance” or “time/period”) to a symbol (e.g., bracket), or describing movements or artifact manipulations that were difficult to capture in diagrams. Although only three of the seven groups chose to draw diagrams of the setup for the second and third slinky experiments, both the slight increase in number of groups electing to draw a diagram as compared to the first slinky experiment (whiteboards seen in Fig. 4.2.2), in addition to the shared features of their diagrams, suggest some development towards a collective understanding of the form and function of diagramming experimental setups.

During the next day (Day 5), I led a follow-up lecture summarizing the two slinky experiments from the previous day. As I began to draw the diagram for the wave speed vs. slinky length experiment, I first drew the slinky (see Fig. 4.2.8a), and then asked the class, “what are the key components of a good, effective diagram” (Unit 1, Fig. 4.2.8). My initial act of drawing the slinky offered students a focal object onto which they suggested how to add other features onto my diagram. In Unit 2, Dustin responded with “arrows,” and then elaborated with the example of labeling the direction of velocity. His response supported the notion that arrows remained a powerful means for conveying both motion, and more specifically the direction of motion, in diagrams. In an attempt to strengthen my students’ use of arrows in their diagrams toward symbolizing other vector quantities in addition to velocity, I asked a broad question: “how do I know what arrows to include [in a diagram]?” (Unit 7). Raymond responded explaining that it depended on what the problem was asking, which Brian further articulated as what you are trying to find or measure (Unit 12). These responses indicate that students recognized that arrows represented variables and measured quantities, but struggled to verbally articulate the general function of arrows in diagrams beyond the example of velocity. By discussing the diagramming process with my class, I aimed at supporting the development of a collective diagrammatical grammar that my students and I could utilize and build upon during future activities, as well as attributing additional value to diagrams as a powerful modality and cultural resource for students to call upon by their own volition.

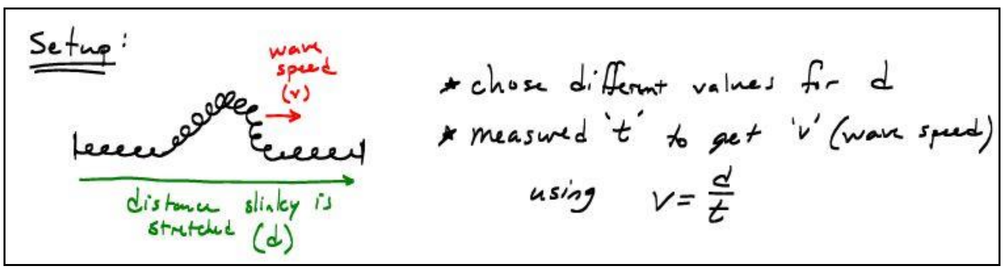
After amplifying students’ ideas for specific characteristics to add to my diagram, I included them in it to model how to diagram the experimental setup (see the original and final versions of the diagram in Fig. 4.2.8). Based on their suggestions, I added the textual captions and labeled arrows seen in the final version of my diagram at the bottom of the transcript in Figure 4.2.8. The transcribed discourse between the original and final version of my diagram positioned the diagrammatic modality as a prominent mode with which our speech develops. Our speech mediated the signs and symbols we elected to add to my diagram. We attributed meaning to its features through our talk about them. Instead of my simply modeling how to draw a diagram, it was critical to our collective development of diagrammatical grammar that I paused and asked questions to provide opportunities for students to discuss which features to include as well as justify their choices. The ideas that students were publically offering afforded them and the rest of the class an opportunity to suggest referents and construct meanings of these features together, which promoted the collective development of our class' diagrammatical grammar and conceptual understandings.



Initial version of my diagram of the wave speed vs. slinky length's experimental setup that is projected in front of the students with ensuing discourse following.

1	Teacher:	What are the key components of drawing a good, effective diagram? (*pauses for hands to raise*) Dustin, yes? (*call s on Dustin*)
2	Dustin:	Arrows.
3	Teacher:	Arrows! Explain what you mean.
4	Dustin:	Uh arrows to show like which way the velocity is going
5	Teacher:	Right, we want arrows. That's good! Now let's be more general about it, like yes we want an arrow to represent speed, but how do we know what arrows to include? What are those arrows showing? Why did he say arrows? And speak in general, like we're talking about in diagrams, but in general, how are arrows used?
6	Robert:	To label uh label the direction of speed or whatever?
7	Teacher:	So arrows show direction and in this case they're labeling the arrow as speed to show the direction of speed. But how do I know when to use speed versus acceleration versus force versus distance versus whatever, how do I know what arrows to include?

8	Raymond:	The type of problem you're answering?
9	Teacher:	Can you elaborate a bit on that?
10	Raymond:	So like if was a kinematic, you'd have to show velocity, like that it's moving
11	Teacher:	(*I sense confusion in many of the students so I take a step back from the discussion and summarize the ideas leading up to this point for a minute, which was omitted from this transcript*) How do I know when to include an arrow for velocity, and when I can just show it moving, but leave out the labeled arrow?
12	Brian:	I think you should label what you're trying to find and what you're trying to measure
13	Teacher:	Yes! So it comes to this, in a good diagram we're gonna put every variable that's relevant, that's either being measured or that's given in a problem like in the text. This is an experiment so we get to chose whatever we measure, those are our givens and if we're trying to calculate something, then we also want to include that 'cause we're trying to show how those variabe relate to each other using a diagram. (*I then add the labeled arrows and accomplanying text to my initial diagram, resulting in the diagram pictured below*)



Final version of my diagram of the wave speed vs. slinky length's that is completed in front of the students by the end of the discourse excerpt shown above.

Figure 4.2.8. (Day 5, 12:18-15:15). Transcript during the follow-up lecture on Slinky Experiments, where I drew a diagram of the experimental setup and had students discuss the key elements of the diagram.

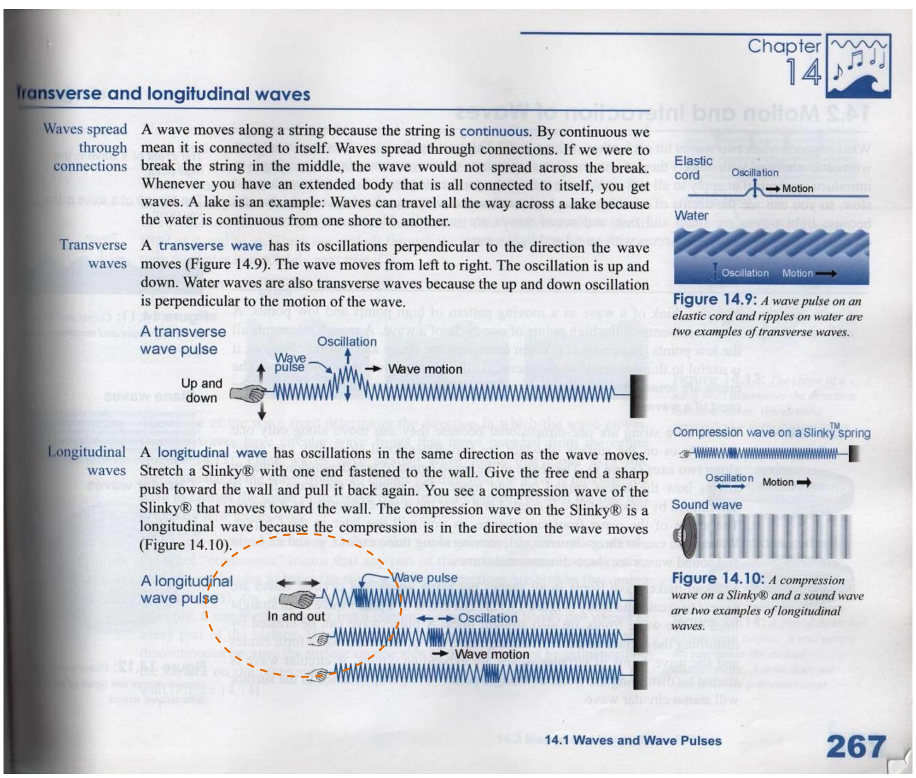
Diagrams were also prevalent in the textbook used in this class (Hsu, 2004) and resembled the diagrams my students and I had drawn because of the similar artifacts and contexts (waves created in a slinky by moving your hand back and forth), and the use of arrows to represent motion. On Day 7, students worked in small groups on a set of practice problems. They had not yet learned the terms *transverse* and *longitudinal*. To introduce the terms, I constructed a problem (Problem #5), seen in its entirety in Fig. 4.2.9, intending that students would seek the definitions and make meaning of the new terms using the context of the problem. I had noted to the students before they began that these terms were in fact new to them, and that they could look up their definitions in their textbook.

5. While hiking along the Des Plaines River, you see a log barely touching the water, creating ripples on the surface. You think of physics and observe that 3 pulses are generated every 0.5 seconds.
(a) What type of wave is this—longitudinal or transverse?
(b) What is its speed on the surface if the pulses are about 8 cm long?

Figure 4.2.9. (Day 7). Problem 5 from the set of practice problems on which students worked together in small groups.

The textbook page that explained transverse and longitudinal waves is shown in Fig. 4.1.12 (Hsu, 2004, p. 267). Zeke, Katie, Addy and Kevin were working together on Problem 5 as Zeke referred to this page for help. Zeke was the only student to look to the textbook, and it seemed that he aimed to find information for the sake of the group and not just his own learning. It is impossible to know what precise elements and parts of the textbook page he focused on, but

I know he only viewed the page for a few seconds before saying, “oh!” as if both realizing the answer and being surprised by it. As seen in Fig. 4.2.10, Zeke then demonstrated for his peers how he made meaning of the textbook’s definition of longitudinal waves saying “it goes like that,” while enacting the textbook’s diagram of a hand moving forwards and backwards with a gesture (as opposed to the side-to-side hand movement done during their slinky experiments). Although it is unclear if the written text or diagram or both in the textbook allowed Zeke to realize this definition, his gesture shown in Fig. 4.2.10 embodies the same hand movement as displayed in the textbook’s diagram, which may be seen in the dotted circle in Fig. 4.1.12.



Chapter 14

Transverse and longitudinal waves

Waves spread through connections — A wave moves along a string because the string is continuous. By continuous we mean it is connected to itself. Waves spread through connections. If we were to break the string in the middle, the wave would not spread across the break. Whenever you have an extended body that is all connected to itself, you get waves. A lake is an example: Waves can travel all the way across a lake because the water is continuous from one shore to another.

Transverse waves — A transverse wave has its oscillations perpendicular to the direction the wave moves (Figure 14.9). The wave moves from left to right. The oscillation is up and down. Water waves are also transverse waves because the up and down oscillation is perpendicular to the motion of the wave.

Longitudinal waves — A longitudinal wave has oscillations in the same direction as the wave moves. Stretch a Slinky® with one end fastened to the wall. Give the free end a sharp push toward the wall and pull it back again. You see a compression wave of the Slinky® that moves toward the wall. The compression wave on the Slinky® is a longitudinal wave because the compression is in the direction the wave moves (Figure 14.10).

Figure 14.9: *A wave pulse on an elastic cord and ripples on water are two examples of transverse waves.*

Figure 14.10: *A compression wave on a Slinky® and a sound wave are two examples of longitudinal waves.*

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Reproduction of Figure 4.1.12. (Day 7). Textbook page on transverse and longitudinal waves (Hsu, 2004, p. 267).

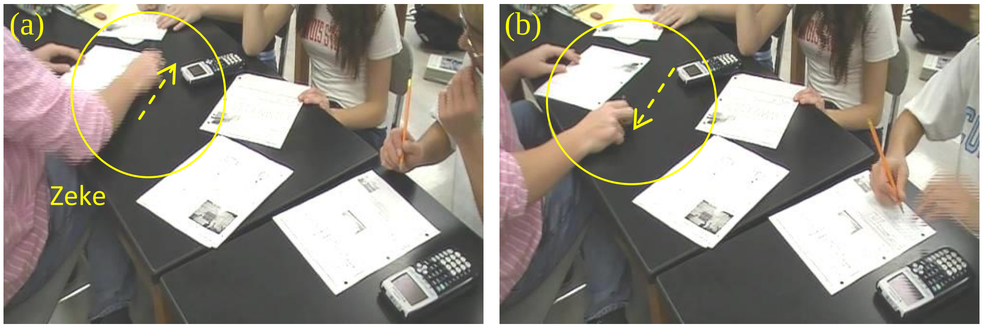


Figure 4.2.10. (Day 7, 39:23). Zeke attempts to explain his interpretation of the textbook's definition of longitudinal waves to the rest of his group by pretending to create a wave in the slinky by (a) moving his hand forwards and (b) backwards as denoted by the dotted arrows.

The group did not initially react to Zeke's idea, but one minute later Katie made the same gesture as Zeke while saying, "it's going like this so it's not amplitude," as she reasoned with Addy which wave characteristic–wavelength or amplitude–would more likely represent the "distance between two successive compressions," which was text from a different practice problem's question. Katie's gesture demonstrates that although she did not react to Zeke's idea initially, she understood it and was able to call upon the gesture when it was appropriate and necessary to do so in a later problem.

The next day (Day 8), a group of two students, Mallory and Megan, chose to draw a diagram to communicate their ideas without my prompting to do so. This was the first instance where a group of students chose to use the diagrammatical modality on their whiteboard to help explain their ideas within a context other than experimental setups. Mallory and Megan had worked together to prepare the whiteboard aimed at explaining their answer to Problem 3 in the set of practice problems they completed together the day before during class. Mallory was later called to publically present her and Megan's whiteboard to the rest of the class (see Fig. 4.2.11). Their problem read, "What happens to the period, wavelength, and speed of a wave on a taut string when the frequency is doubled? *Explain.*" Mallory and Megan elected to use a diagram and text to describe the characteristic of frequency, and particularly its relationship with wavelength in order to answer the question.

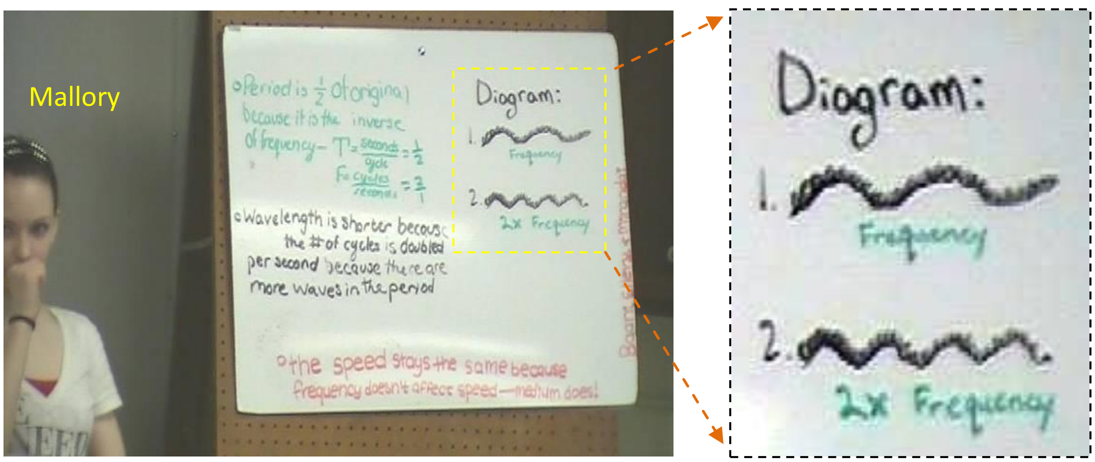


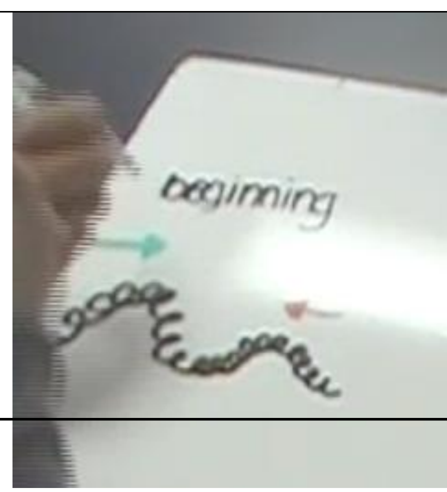
Figure 4.2.11. (Day 8, 24:20). Mallory (Group 3) uses her group's whiteboard to help explain their solutions to Problem 3: "What happens to the period, wavelength, and speed of a wave on a taut string when the frequency is doubled? *Explain.*"

When Mallory presented the whiteboard to the class, she read the text as she pointed to the diagram to support the text. Their text included: "period is ½ of original because it is the inverse of the frequency"; "wavelength is shorter because the # of cycles per second is doubled because there are more waves in the period"; and "the speed stays the same because frequency doesn't affect speed–medium does!" (Fig. 4.2.11). Mallory pointed to the diagram as she said that the wavelength would be shorter as a justification for her verbal answer. The text answers the question, but the diagram provides the rationale for their answer. Her deictic gesture to the diagram, which displays the two waves–one with twice the frequency and half the wavelength as the other, was simultaneous to her answer that the wavelength would be shorter. The diagram represents a scientifically correct definition of wavelength and an inverse relationship between frequency and wavelength, and accurately provides rationale for their answer written next to it.

Their phrase: “more waves in the period,” incorrectly used the scientific term “period.” Period is the time for one oscillation, and they had already stated that the wave’s period would be half of the original. However, taking “period” to mean “amount of time” in colloquial, everyday, and lifeworld language explains the students’ use of this word to communicate that there are more waves in the same period of time.

Although, the students’ text focused directly on how the wave characteristics (i.e., period, wavelength, and speed) changed in response to the frequency doubling (which is what the problem was asking), their diagram focused on depicting what doubling the frequency looks like for waves in a slinky, which was a familiar context that they had engaged with many times before. Once doubling the frequency was visualized, the subsequent changes to the other wave characteristics could be noted, and noted in a visual way. Whereas the text focused directly on the wave characteristics other than frequency, the diagram focused directly on the frequency and could allow the reader to indirectly infer the consequences of doubling of frequency to the other wave characteristics. The diagram seen in Figure 4.2.11 shows a slinky that had two wave cycles along its length vertically juxtaposed with a slinky that had four wave cycles along its length, which captures the idea that frequency was doubled. The vertical alignment of these two slinkies allowed for representation of effects of frequency change (i.e., more wave cycles) on wavelength (i.e., shorter wavelength), which were highlighted in the text on the students' whiteboard. Mallory and Megan's choice to use a diagram suggested that they valued diagrams as a modality to meaningfully communicate their ideas, and their conceptual understanding was represented within the diagrammatical modality.

On the following day (Day 9) when students were conducting slinky experiments to investigate the new topic of wave interference, the focal group negotiated the collective production of a diagram on their whiteboard where they were presenting their conclusions from the experiment. Figure 4.2.12 shows the multimodal discourse in the focal group and all groups' whiteboards are presented in Figure 4.2.13-14.

1	Katie:	So like beginning, middle and end, right?	
2	Kevin:	Yeah. (*Katie writes "beginning," "middle," and "end" across the top of the whiteboard*) So at the beginning the big wave an the small wave travel towards each other and at the middle they create a superwave and then at the end they were a little bit smaller.	
3	Katie:	I'm gonna make it really obvious. (*Katie is likely referring to making it really obvious that they used a small and large wave pulse in order to distinguish between the two pulses. Immediately after her utterance, she draws a large slinky wave and a smaller wave*). So I'll like draw an arrow going that way and an arrow going that way (*points to each wave*).	

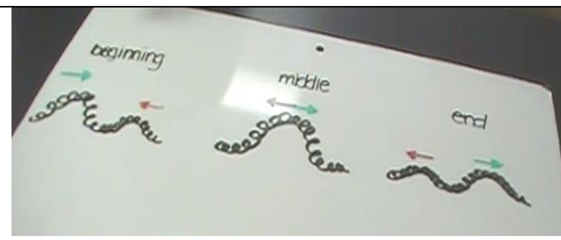
4	Kevin:	Yeah. (*Katie draws two different colored arrows, one above each wave to denote their propagation towards each other as seen in the picutre to the right*).	
5	Katie:	(*Katie draws one much larger wave under "middle"*) So this is still going this way (*gestures to the right as if she is going to draw a green arrow to the right*)	
6	Kevin:	And then we can draw like a red arrow interfering.	
7	Katie:	Like that?	
8	Kevin:	Yeah.	
9	Katie:	And then.	
10	Kevin:	And then the ending one.	
11	Katie:	The small one is still going this way? (*gestures left*) (*Katie draws a little wave*) That's just a little smaller. (*Katie draws a the big wave now on the other side, see picture to the right*).	

Figure 4.2.12. (Day 9, 22:20-24:17). Multimodal transcript of the focal group's interactions while drawing of a diagram to present their experimental findings during a lesson on wave interference. Addy is videotaping.

Students were to conduct experiments to answer two questions: (1) will waves pass through each other completely, do they bounce off completely, or a little bit of both?; (2) how will waves' amplitudes be affected at the instant they interact—nothing, create a gigantic wave, completely destroy each other, etc.? The focal group created an experiment in which they simultaneously created one large and one small wave at opposing ends of a slinky that traveled towards each other, and found that the waves passed through each other. They used a large and small (amplitude) wave in order to distinguish the two waves from one another. Katie immediately elected to diagram what they did with the slinky in order to present their findings on a whiteboard, which forced her to choose critical instances to capture in the diagram. In Unit 1, she suggested that they drew their setup at three different times–the *beginning*, *middle* or during the waves' interaction, and *end*. Depicting these three instances enabled their group to create snapshots of their experimental setup via the diagrams, which served as epistemological affordances (Bezemer & Kress, 2008) to organize and exhibit their conclusions. The beginning and end diagrams prove that the two wave pulses pass through each other, while the middle diagram supports their conclusion that the two pulses momentarily combine to make one even larger wave as they pass through one another.

In Unit 3 of the transcript in Figure 4.2.12, Katie suggested drawing arrows to show the direction the waves traveled. Her use of arrows to represent the motion of the waves is an element that students and I had emphasized as an important feature of diagrams earlier, namely during the post-experiment discussion captured in the transcript in Figure 4.2.8. Moreover, she color-coded the arrows to keep the arrows, and waves to which they corresponded, distinct from one another that could reduce ambiguity for the reader. If the arrows were all the same color, it would have been less clear that the waves passed though each other as opposed to bouncing off. The idea of waves passing through each other was further reinforced by the group's decision to create and depict in their diagram one small and one large wave so they can be differentiated from each other. Since their diagram captured the way in which their experiment unfolded and the actual data they observed, it offered the rest of the class the same evidence that the focal group used to derive their conclusions. Katie's choice to foreground diagrams as well as her choice to draw these diagrams using features such as arrows, which we had previously discussed, demonstrated her understanding of diagrammatic grammar.

After every group finished preparing their whiteboards, I chose three of the seven boards to display publically as focal objects for a class discussion (see Fig. 4.2.13). I chose these three boards to provide our class an opportunity to discuss artifacts of groups that had different methods of experimentation and contrasting findings, and to not overwhelm students with too many boards. Figure 4.2.14 shows the other four whiteboards that were not displayed publically for discussion, which provide insight into the diagrammatical practices of the class.

The focal group (Fig. 4.2.13a) and the group with the board shown in Fig. 4.2.13b both concluded that the waves passed through each other. They both produced two pulses that were distinct from each other. As previously mentioned, the focal group made one large and one small wave to make this distinction. However, the group whose board is seen in Fig. 4.2.13b diagrammed two experimental setups. One setup utilized one large and one small amplitude wave, similar to the focal group, except that the waves were inverted such that one pulse was created with a left-right hand movement at one end of the slinky whereas the other pulse was created with a right-left hand movement at the other end of the slinky. Their other setup followed the same premise of sending two distinct waves toward each other, but in this case, one was a transverse wave and the other a longitudinal wave. The board shown in Fig. 4.2.13c presented an incorrect conclusion that the two waves bounce off each other, which is a common student misconception regarding wave interference. Their diagram depicted two identical waves that collided and bounced off. Their use of two identical waves was the source of their mistake, which was made evident in their diagram. The waves were indistinguishable, and thus allowed for ambiguous interpretations. Although they actually passed through one another, they *appeared* to these students to bounce off each other. The diagramming allowed for the other students and me to immediately recognize what this group, and other groups, did experimentally that led them to their conclusions. We were able to discuss the different conclusions in light of the diagrams. I had asked them to justify their claims, so their choosing to diagram signifies my students had constructed diagrams as valuable tools for describing experimental setups. Moreover, the ways in which students diagrammed, and their shared diagrammatical practices in particular, provided insights into the development of my class's collective diagrammatical grammar.

The other four groups' whiteboards were not displayed for discussion, but were analyzed for the purposes of this study (see Fig. 4.2.14). Examining all seven boards showed that arrows were a prominent diagrammatic characteristic, and five of the seven boards included arrows. All but one of those five groups used arrows to represent motion and the direction of that motion. That group (Fig. 4.2.14c) used arrows as an interval representing amplitude, which the group claimed, in the text corresponding to the diagram, "flattened out" as the two inverted waves passed through each other. On that board, the text was supported by the middle diagram, labeled "contact," which displayed a flattened out wave as the two waves passed through each other. Before that moment (labeled "start"), and after (labeled "end"), the waves are shown to have amplitude denoted by arrows, which further explicated the students' rationale for the conclusion shared in the text on their board.

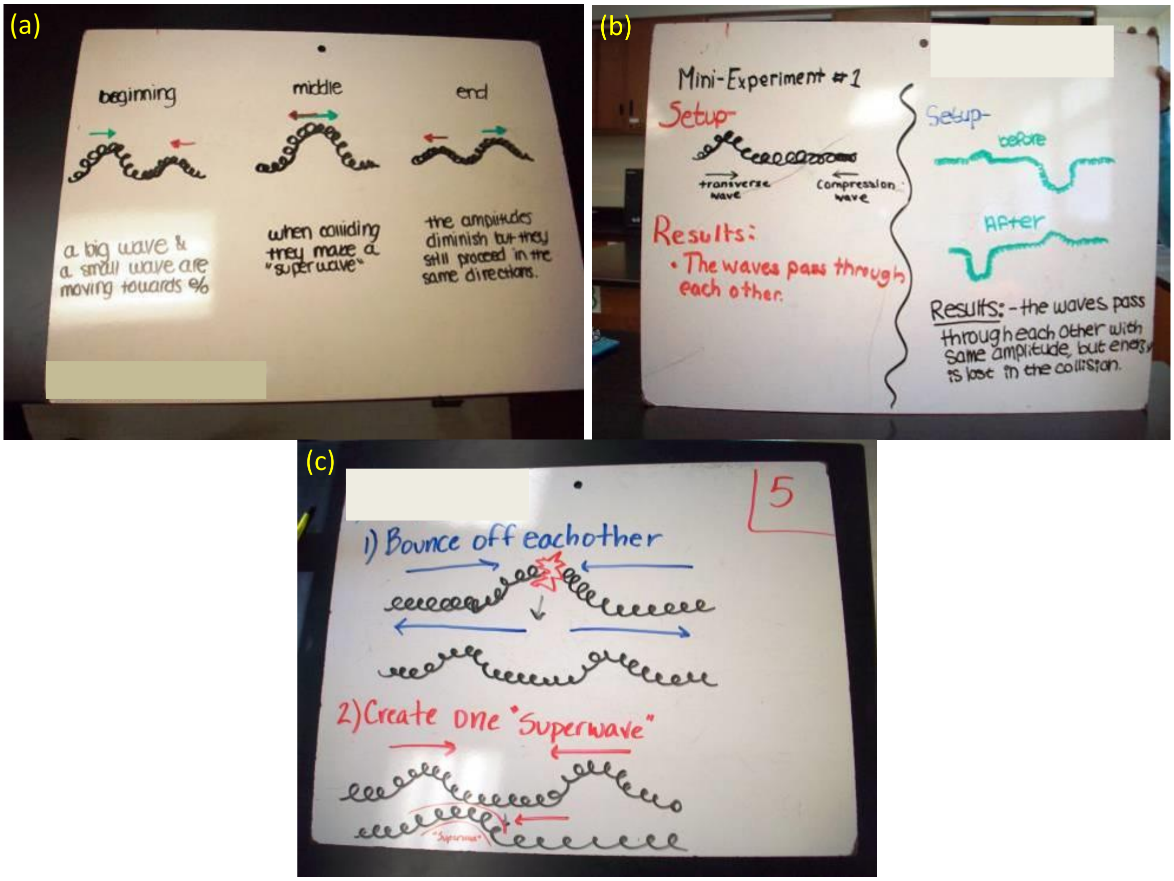


Figure 4.2.13. (Day 9). The three whiteboards summarizing students' ideas concerning wave interference that are publically displayed as focal objects for a class discussion.

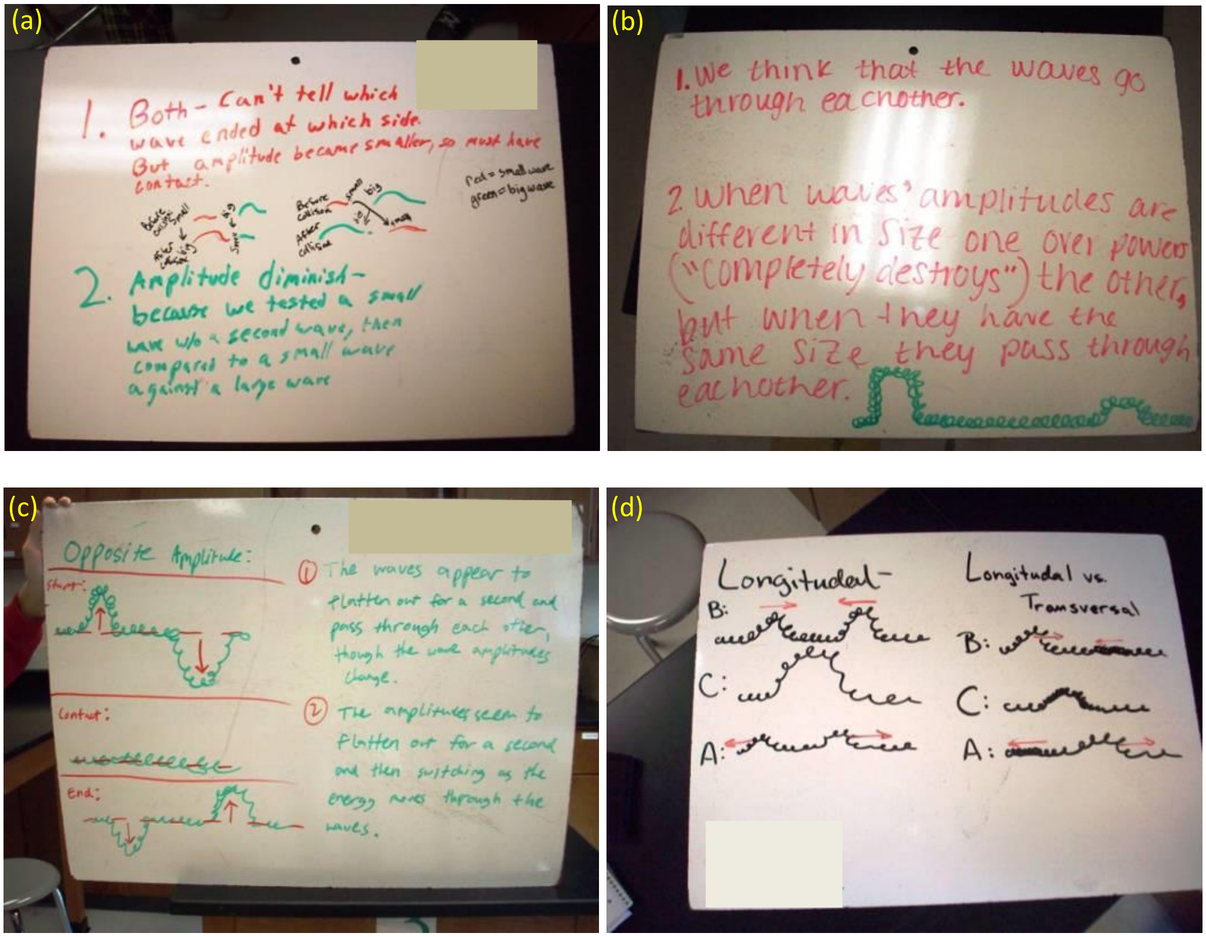


Figure 4.2.14. (Day 9). The four whiteboards summarizing students' ideas concerning wave interference that are not publically displayed.

Diagrams had been prominent during experimental activities, such as during the previous slinky experiments, especially as a means of presenting the experimental setup. In this lesson, students were again conducting experiments using slinkies, and called upon diagrams and text to communicate their findings on their whiteboards. This lesson's purpose (i.e., to explain how two wave pulses interacted or interfered with each other) differed from the purpose of the previous slinky experiments (i.e., to derive relationships between two wave characteristics). The explanatory nature of this task promoted the use of qualitative data such as observations, which students chose to describe using linguistic and diagrammatical modes.

The diagrams on all of the whiteboards were foregrounded alongside text, but with varying degrees of prominence–text dominated in Figure 4.2.14b, diagram dominated in Figure 4.2.13c and Figure 4.2.14d, and both text and diagrams were prominent in Figures 4.2.13a and 4.2.14c. The group with the board shown in Figure 4.2.13c chose to diagram the action they briefly described with words in such a way that their diagram and text reinforced each other. The diagram both demonstrated their conclusion stated in the text (i.e., “bounce off each other”) and justified their claim by showing what they did with the artifacts and what they observed as a result. The text alone conveyed the same idea, but the diagram intertwined the idea with the artifacts and observations they made to generate the idea. Thus, the meaning made by the diagram differed slightly from meaning made by the text, and together, text and diagram, represented a richer idea.

Much of the writing on these boards was either captions or labels of the students’ diagrams. The captions either called attention to particular aspects of their diagrams or linguistically summarized meanings the authors intended to portray with the diagrams to minimize the reader’s interpretive ambiguity. For instance, the group with the board shown in Fig. 4.2.14c directly answered with text the two questions guiding the experiment, but used one diagram to show what they did and observed. Their answer to the first question was that “the waves appear to flatten out for a second and pass through each other, though the wave amplitudes change.” As noted above, the middle diagram labeled “contact” showed a flattened out wave. The before/after diagrams labeled “start” and “end” suggested that the waves passed through one another, and that the waves' amplitudes changed between the start and end as described in the text. Moreover, the diagram depicted the amplitudes at the end as smaller than the ones at the start. This was an epistemological affordance of the diagrams, showing *how* the amplitudes change, which the text did not describe. Their text could have stated that the amplitudes decreased, but students could not diagram the changing amplitude without showing the way in which it changed. The text and diagram formed a complementary relationship regarding meaning making. Furthermore, without the text to call the reader's attention to this change, it would have been likely for the reader to overlook this detail.

Their answer to the second question, which was about how the waves' amplitudes might be affected at the instant they interact, stated that "the amplitudes seem to flatten out for a second and then switching as the energy moves through the waves." The second part of this answer is unclear in terms of the students' use of the word *switching*. Since the students used two waves of similar amplitudes, as depicted in the diagram, and the same color to depict the two waves, their diagram did not clarify what they meant by *switching* in their text. At least two possible interpretations of the word *switching* should be considered. One is that the two waves pass through each other, momentarily destruct at the instant they pass, and switch places as they continue in their respective directions (the wave initially on the left side switched to the right after passing through, and vice versa), which a scientifically accurate understanding of the phenomenon. The other is that the two waves, at the time of the contact destruct, but bounce off each other and switch amplitudes, which is a scientifically inaccurate understanding, and one that I have encountered several times during my physics teaching career. Given the students' answer to the first question, the former interpretation is more likely. Moreover, the group's reference in their text that "energy moves through the waves" can be interpreted as a justification of the diminished amplitudes they depicted in their diagram for the stage labeled “end” as opposed to that labeled “start.” As the waves travel through each other, there is a decrease of energy that maps onto the wave amplitudes.

Other than captions, text was also used as labels. The textual labels both called attention to critical features of a diagram and named these features. Naming features may contribute additional meaning to the diagram by diminishing the range of interpretive choices that the reader has to make. For example, in Fig. 4.2.13b, the two waves and their respective arrows were labeled as “transverse wave” and “compression wave.” If the compressional wave was not named, the reader could have easily overlooked this feature based on how subtle this was depicted. In addition, the naming of the two waves focused the reader’s attention to the difference in the two opposing waves. The scientific terms “traverse wave” and “compression wave” imply differences in the relation between the direction of movement of the wave source and the direction of the wave propagation.

On the next day (Day 10), the class period began with a standing wave apparatus set up in front of the class. Standing waves only exist at certain frequencies in which the wave moving to the left and the reflected wave moving to the right are aligned thereby creating a wave that appears stationary, or *standing*. I initiated a discussion by asking students for their ideas as to why there appeared to be stationary points (i.e., nodes) within the waves in the string. Zeke volunteered to answer, and used speech and gestures to explain his ideas, but struggled to make his points clear for the class. His speech and use of gestures enacting his idea suggested that he was “constructing” a diagram in the air based on what he envisioned, since he could not draw it being seated in the back of the classroom. His gesturing at this time was previously discussed in Section 4.1, and can be seen in Fig. 4.1.16. Recognizing that Zeke was attempting to diagram, but lacked the semiotic resources to do so, I asked him to come up to the front and draw the diagram he was envisioning for the class. As he drew the diagram seen in Fig. 4.2.15, he had some difficulty talking about it and muttered inaudibly as if talking to himself. He drew the red-colored wave from left to right and then the purple wave from right to left, which might have emphasized to the rest of the students watching him the directional aspects of those waves. These were incorporated in the construction of the diagram, which otherwise did not show any movement. There were no arrows. The specific direction of each wave is not as important in this context, which might explain why Zeke chose not to label the diagram with any arrows. On the other hand, the fact that they were traveling in opposite directions relative to one another is important for understanding that one wave is a reflection that is superimposed over the incident wave, which explains the existence of nodes. This idea was not represented in his diagram but was initially described by his iconic gesturing seen in Fig. 4.1.15. Zeke finished the diagram by drawing large dots at the stationary points in his diagram while saying, “and that’s where they intersect.” As he spoke, he simultaneously gestured by crossing his hands in the shape of an ‘X’ as an enactment of the red and purple (incident and reflected) waves’ intersection at a node. The direction in which he drew the red and purple waves during the construction of his diagram, coupled with his iconic gestures and speech from his seat before diagramming, suggested that he understood the idea that one of the waves reflected and therefore headed in opposite directions relative to one other. His speech and gesture during his construction of the diagram complemented the diagram by calling the class’ attention to the point of intersection between the two waves, and then gesturing to show the relative position of the waves at the node as the passed through each other. He used color-coding (red and purple) to demarcate the incident and reflected waves, and then made large dots at the nodes to make those locations more pronounced.

Since standing waves were an entirely new context, Zeke seems to have used diagramming as a modality to anchor his ideas about the standing waves context, and in particular why the stationary points (nodes) existed. Diagramming was a critical modality for his engagement because he lacked the scientific language such as *nodes*, *antinodes*, and *incident* and *reflected* waves to verbally or textually articulate his ideas succinctly.

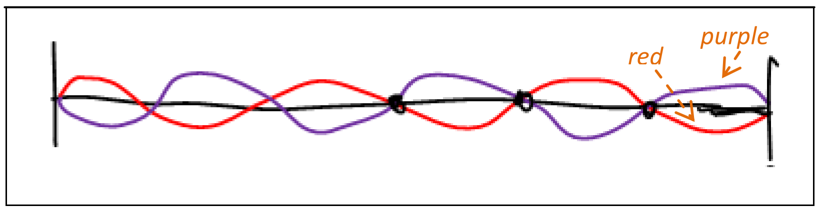


Figure 4.2.15. (Day 10, 7:20). Zeke's original diagram on a standing wave used to aid his explanation for the existence of nodes.

Summary

This section aimed at tracking the evolution of the form and function of diagrams used in my class. The specific forms of diagrams used and the ways in which they functioned to provide my students opportunities for meaning making constituted the diagrammatical grammar that my class explored. There were several critical characteristics of the diagrammatical grammar that my students and I co-constructed over the instructional unit, including: iconic depictions of artifacts, selection of critical instances to capture, artifact positioning and manipulation, representation of measured values or variables using arrows and brackets, and textual labels or captions.

The development of diagrams as a prominent modality for meaning making took place as my students and I continuously diagrammed across activities. The students were initially led to diagram when I asked them to draw a wave during the first lesson (Fig. 4.2.1). The most common depiction emerging from students during this lesson was a wavy line, which was already familiar to them as an iconic representation of water waves. The wavy line diagram depicted water waves at an instant in time, which became the focus of our discussion on perspective or the point of view in diagrams (e.g., above view or side view). This was necessary for students to meaningfully create and read diagrams throughout the unit. Diagramming during the first slinky experiment was not prevalent, but the few diagrams produced functioned as public examples of diagramming that utilized perspective and spatial layouts of experimental artifacts. Moreover, one of the diagrams included the wavy line to depict waves in a slinky, which reflected application of the previous day's diagram of water waves to a new wave context (i.e., waves in a slinky).

Diagrams of experimental artifacts, and their relative positions within various experimental setups, became integral to students' experimental investigations of waves. The act of diagramming created epistemological affordances for students to analyze particular instances, and consider details at those particular instances that students might not have otherwise engaged with and/or fully represented, such as *how* amplitude changed (Fig. 4.2.14c). I promoted their diagramming of experimental setups in particular to encourage not only their choice of this modality, but to also co-construct a collective diagrammatical grammar. I drew diagrams during lectures and whole-class discussions (e.g., Fig. 4.2.3 and 4.2.8), and asked students to draw diagrams for everyone to see (e.g., Fig. 4.2.4 and 4.2.15), of which we made meaning together as a class.

When diagramming a context, students had to select an instant or instances to depict. When carefully chosen, these often reflect critical instances in dynamic contexts such as *before* and *after* (or even *during*) as students did for their investigations of wave interference (Fig. 4.2.13-14). Students' ability to choose these instances reflected an understanding of how to analyze and simplify an event in order to explain it in more detail. They were forced to recognize when key moments occurred regarding the scientific concepts with which they were engaging. In the study of wave interference, students depicted the moment that two waves initially heading toward one another crossed in order to explain the way in which they interacted. Moreover, once students chose an instance to diagram, the motion was captured and frozen in time, which provided distinct epistemological affordances as the features of the diagram were constructed, negotiated, and labeled by the authors and then interpreted by the readers.

Initial student diagrams were often iconic depictions of concrete objects, such as water (Fig. 4.2.1) and slinkies (Fig. 4.2.2b), with waves traveling through them and experimental artifacts (Fig. 4.2.2a). As students developed a collective grammar for diagramming, they became increasingly able to depict more elaborate details within their diagrams, which further explicated their ideas and encouraged meaning making among students. Such details included capturing experimental artifacts' manipulations and actions that were often represented by arrows, as was the case in Raymond's and then the focal group's diagrams shown in Unit 3 of Fig. 4.2.4 and Unit 8 of Fig. 4.2.5, respectively. Arrows were an integral part of the diagrammatical modality throughout the unit. Aside from representing movement and artifact manipulation, arrows also depicted measured vector quantities, such as amplitude (Fig. 4.2.3 and 4.2.14c) and speed (Fig. 4.2.3, 4.2.8b, 4.2.13a-c, and 4.2.14d), and added directional aspects to motion when depicting speed or movement. My students also used, without my modeling or suggestion, brackets to depict intervals, such as distance (Fig. 4.2.6a, b, & 4.2.7a) and time (Unit 4, Fig. 4.2.5).

The other prominent diagrammatical characteristic developed as part of the diagrammatical grammar was text written in the form of labels and captions within a diagram. Although text is a linguistic mode that often acts in isolation from other modes, when used within diagrams, text can be treated as a diagrammatic characteristic that adds meaning to both the other diagrammatical characteristics and the diagram in general. Labels, such as a numerical value or variable written next to an arrow, namely the brackets labeled "Δx" (Fig. 4.2.6a, b) or the naming of "transverse" and "longitudinal" waves (Fig. 4.2.14b), more explicitly denote the author's representational intentions. Captions were students' textual statements corresponding to aspects of their diagram. Mallory and Megan used captions underneath their diagrams (Fig. 4.2.12), which included "frequency" and "2x frequency," in order to focus the class' attention to the specific concept or meaning they intended for their diagram to portray. These functioned as a way for the author of the diagrams to interpret the diagram minimizing the interpretive flexibility associated with their diagrams. The captions reduced the many meaning potentials through which a reader could interpret their diagram to converge on the author's intended meaning. In the case of Mallory and Megan, they intended to depict how doubling the frequency of waves in a slinky would appear using a diagram in order to justify their claim that wavelength would be halved if frequency were doubled. Critical instances were also labeled with captions to name the instant or denote when the instant occurred relative to the entire motion represented by the diagram, such as "beginning," "during," and "end" (Fig. 4.2.13a & 4.2.14c).

Students took the initiative to diagram when they felt diagrams would benefit their articulation of ideas. When students conducted their slinky experiments, they chose whether or not to diagram their experimental setups on their whiteboards. Both the abundance of those groups who chose to diagram and the quality of the diagrams (i.e., sophistication of diagrammatical features and use of semiotic resources) they produced improved throughout the unit as a collective diagrammatical grammar was discursively developed over time. Diagramming became a norm of my class's multimodal discourse, a part of my classroom's cultural practices for students to call upon whenever they desired as an abbreviated or succinct way of visually depicting an idea, context, or event. As compared to the whiteboards produced after the first slinky experiment (Fig. 4.2.2), the students' initiative to construct diagrams dramatically increased for those whiteboards students prepared later in the unit (Fig. 4.2.13-14). The diagrams being drawn also became more detailed in accordance to the diagrammatical grammar that students developed collectively through the continuous use of diagrams across activities. Although the nature of the activities likely motivated their electing to diagram, the diagrams presented in this section reveal an increase in the detail and sophistication of diagrammatical features, as well as students' initiative to choose to diagram when I did not prompt them to do so. For example, many of the groups included textual labels and captions to accompany their diagrams, and used arrows to denote not only that the waves were propagating, but also the direction they traveled. At the end of the unit, students were able to utilize diagrams to consider waves in circumstances in which waves were not readily observable (Fig. 4.2.15).

Zeke's ability to diagram the standing wave in order to better articulate his conceptions when speech and gesture could not, highlight a potential benefit to providing students an omnipresent space for spontaneous diagramming. Since I intended for diagramming to be a primary modality in my class' culture of doing science and multimodal discourse, I needed to provide my students with continual access to diagramming for whenever *they* elected to do so. I wanted students to always have available opportunities to diagram their ideas to one another whenever they elected to do so. I promoted diagramming by recognizing when students struggled to communicate using speech and gestures alone, and asking them to diagram what they envisioned as was the case with Zeke. I also supported their use of diagrams by asking them to whiteboard their findings on many different occasions. The open space on the whiteboards and multiple-colored dry-erase markers afforded them the opportunity to draw diagrams that would be shared with the rest of the class. During my lectures, I also modeled the use of diagrams to assign value and guide the development of diagrammatical grammar which they could use in future activities, as well as I led discussions explicitly focused on diagramming practices in the context of their slinky experiments. All of these shaped the form and function of diagramming in my class that evolved through the unit.

Diagrams also influenced the conceptual development, or ideational engagement, of my students, in addition to offering a window into their understanding. For instance, as the teacher, I was able to assess Zeke's understanding of standing waves based on his ideational engagement with the diagram (Fig 4.2.16) even though his peers likely did not all follow his muddled speech and gesturing about the diagram. As students in my class diagrammed, wave concepts were shaped and developed via the different meaning potentials and epistemological affordances that diagrams provided. Using diagrams, my students constructed an individual and collective understanding of not only *what* aspects of a phenomenon or event were important to depict, but also *how* to utilize semiotic resources to represent them in diagrams.

V. CONCEPT DEVELOPMENT IN THE CONTEXT OF MULTIMODALITY

Wave characteristics

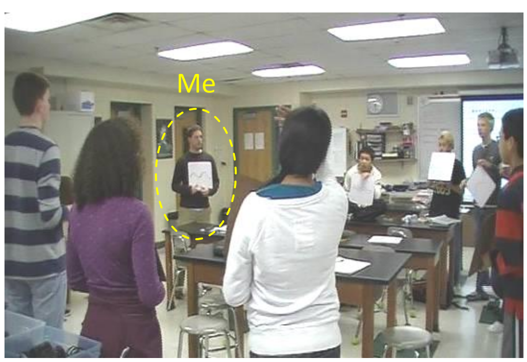
Multimodality played an important role in my students' development of conceptual understandings of wave characteristics. Students interacted with each other, teacher, and ideas, using linguistic and non-linguistic modes, including gestures, diagrams, graphs, and classroom artifact-manipulation. In previous sections, I presented ways in which two modes (gesturing and diagramming), which became salient in my classroom, developed over time, shaping and being shaped by the classroom participants' ideas about waves. In this section, I present ways in which the development of concepts related to wave characteristics took place across modalities and instructional activities, showing the intricate intertwining of various modes and the ebb and flow of ideas across modalities.

The Ebb and Flow of Concepts Across Multiple Modes

A common representation of waves is a wavy line in which my students and I engaged throughout the entire instructional unit. My students' drawings of waves on the first day of the unit largely consisted of wavy lines, which they linked to water waves that they had amply experienced in their everyday life. This wavy line became a critical semiotic resource for the development of ideas such as the propagational and oscillatory motions of waves, as well as amplitude, wavelength, period, and frequency. Wavy-line diagrams provided students an opportunity to engage with, and make meaning of, wave characteristics in addition to language used to communicate about these concepts.

I began the waves unit in my class by having students individually respond on paper to the following three tasks: (1) draw a wave; (2) what makes something a wave?; and (3) write down 4 examples of waves. The order of these questions was important. I wanted their drawing of a wave to precede their writing of a definition. Students had to call upon prior knowledge and experiences with waves within any mode (such as pictures, photographs, observations, diagrams, gestures, or language) in order to draw a wave. The act of drawing a wave promoted not only their depicting the wave as one entity, but its constituents and characteristics as well, for which students lacked the academic language to describe at that time, and which would be called upon later as the unit progressed. Students could call upon their drawing's features as they constructed next their linguistic definition of a wave for their next question.

Since I intended to have my students identify commonalities among their drawings, I had asked them to draw their waves both on paper, to turn in, and on a small 1x1 ft. whiteboard. I had also created a whiteboard with a wavy line that I anticipated many students would draw. We all stood up in a circular arrangement and displayed our whiteboards for each other to see in a gallery view (see Fig. 4.2.1, inserted below too for reader's convenience). As my students and I simultaneously turned over our boards to display our drawings, I asked the students to look at each other's drawings and identify patterns. The class and I were able to come up with three different variations for a wave drawing, all shown in Figure 5.1.1.



Reproduction of Figure 4.2.1. (Day 1, 9:17). Gallery-view of students' and my wave diagrams during the 1st lesson of the unit.

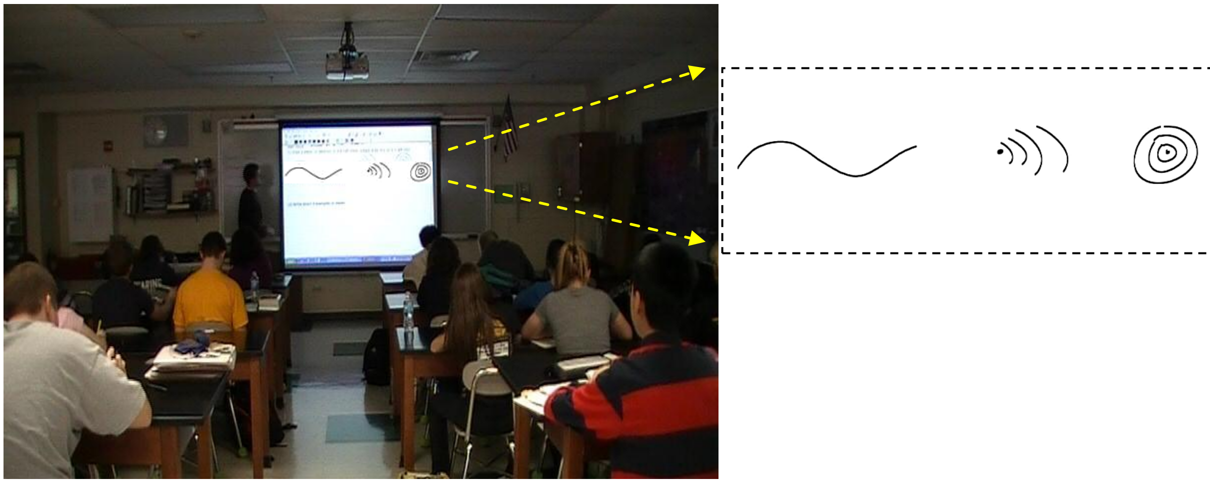


Figure 5.1.1. (Day 1, 14:56). I draw the three examples of student-generated wave drawings from our gallery view and project them in front of the class.

After the students returned to their seats, I drew the three most common student-suggested drawings, seen in Figure 5.1.1, as focal objects for a whole-class discussion. In order to better understand what meanings each of these drawings carried for different students, I asked students to explain why these drawings are different yet still able to depict a wave. Each student's interpretation publically refined and explicated the collective meaning of the three diagrams for the class.

The three students' ideas shown in Figure 5.1.1 all contain the same concept of perspective (i.e., above view vs. side view). Perspective was an important concept when reading the three drawings in order for the students to successfully link the three drawings as all representing the same wave. Moreover, different points of view afforded more or less prominence to different wave characteristics (such as amplitude, which is visible only in the side view). A collective understanding of the perspective from which to view the drawings was essential for defining wave characteristics. As students continued to create and interpret diagrams, they would have to apply perspective in order to make meaning of the concepts being diagrammed, which will be discussed later in more detail.

Students' past everyday experiences with water influenced many of their drawings, evidenced by students stating that their drawings were depicting a water wave, as previously discussed (e.g., see Fig. 4.1.1). Leslie used this real-world example to help situate her interpretation in Unit 4 of the transcript shown in Fig 5.1.2. Her comment first attached the word *ripple* to the concentric circles diagram seen on the right of Fig. 5.1.1. Ripple is a word often associated with waves, and water waves in particular, and provides the context here for Leslie's meaning-making of the concentric circles wave diagram.

From their interpretations of these diagrams, the students began to differentiate between the macro or micro perspectives of waves (i.e., the *macro* propagational motion of the pulse as opposed to the *micro* back and forth motion of the source and particles within the medium). For example, in Unit 1 of Fig. 5.1.2, Dustin described the wavy nature of the line to represent a wave's motion as "goes up and down," which resembled the back and forth or micro wave perspective. He then alluded to the propagational or macro wave perspective by describing the ripple-shaped drawing's motion as "goes out [from the center]."

The next day (Day 2), students conducted experiments in groups each using a long metal slinky with which they were to represent the relationship between a wave's speed and its height using a graph and mathematical function. Each three-person group prepared a large 2x3-ft. whiteboard summarizing their results, which were to be publically displayed as focal objects for a whole-class discussion following the experiment. The four groups whose boards I chose to display were previously discussed in Fig. 4.2.2, but are reproduced below too for readers' ease.

1	Dustin:	The one on the left [wavy line] goes up and down and the one on the right [ripple-shaped wave] goes out.
	[I ask for further explanation about the movement in each wave drawing, particularly moving from what point?]	
2	Oliver:	Maybe the one on the left is a horizontal view and the one on the right is a veritcal view from above
3	Teacher:	Ahh very interesting idea. So could these [drawings] be the same thing or are they different?
4	Leslie:	It’s kinda like the one with the circles going out from the dot, it’s kind of like an over view and an example is you look at water the ripples go out but if you look at it from the side the water goes up and down
5	Teacher:	Yeah, so they could be the same thing and you’re using the example of water

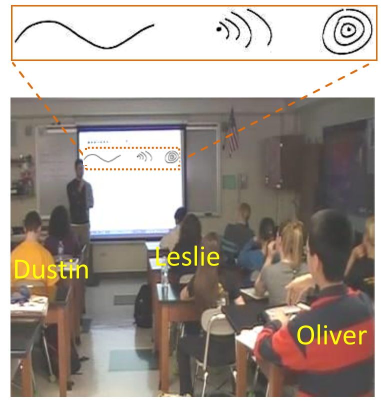
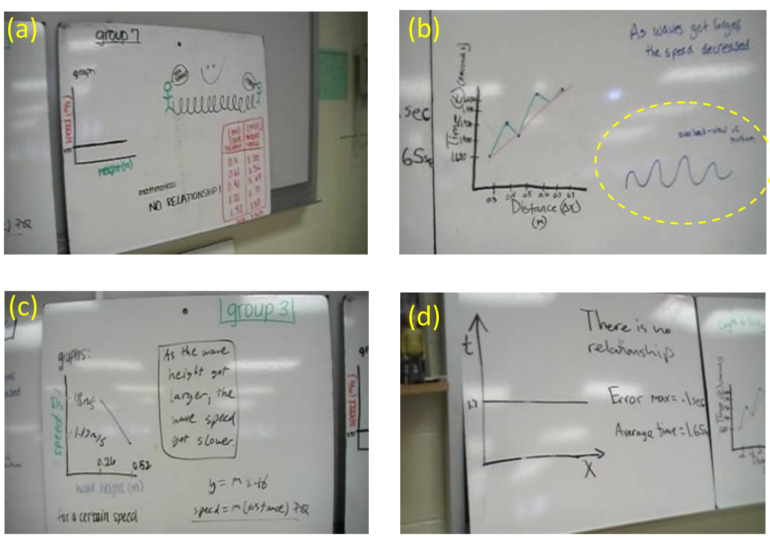


Figure 5.1.2. (Day 1, 14:45-18:35). Students contrast three different wave drawings.



Reproduction of Figure 4.2.2. (end of Day 2). Student-groups’ whiteboards summarizing wave speed vs. wave height experiment. (a) Focal group’s board. (b) Text accompanying the wavy line specifies, “overhead view of motion.” (c, d) No diagram of experimental setup.

Regarding wave characteristics, the instructional goal of this experiment was for students to develop the concepts of amplitude and wave speed, with which they were not yet familiar, by engaging with ideas using language (their own colloquial language), artifacts, and tables to organize their measurements of these quantities. Since we had focused on diagramming waves during the previous day, I was interested in seeing how the students might call upon the diagrams as they described their investigation and findings. I did not explicitly ask students to diagram, but provided the semiotic resources (whiteboard, dry-erase markers) for them to do so if they wished. I did not require diagrams because I wanted to see if students considered diagramming as a useful modality for describing waves, particularly in light of yesterday's discussion. I wanted to see if and which aspects of the previous day's diagrams would be called upon in this experimental context. Only two groups whose boards are seen in 4.2.2a,b constructed diagrams, but for different purposes. Fig. 4.2.2a showed the spatial positioning of the participants in relation to the slinky while they were creating waves, but did not show how the waves produced embodied any wave characteristics.

Figure 4.2.2b did not depict the participants or how the waves were created, but incorporated the concept of perspective to represent the waves generated in the slinky. The idea of perspective was brought up in the previous day's discussion, in which the *above*-view perspective best described the ripple drawing while the *side*-view was attributed to the wavy line. However, the diagram in Fig. 4.2.2b correctly described this drawing's perspective as an above- or "overhead-view of [the] motion," which was not the same perspective attributed to the wavy line during the previous day's discussion, and, therefore, suggesting that this diagram was an extension of the concept of perspective in this new context, and not merely a rote reproduction of a wavy line. This team was the only one that chose to draw a wavy line. If considered by itself, their referent for this wavy line and its intended meaning might be unclear; however, this wavy line depicted an above-view of the long metal slinky as continuous wave pulses were created within it. The textual label over the diagram (i.e., “over-head view of motion”) explicitly communicated the team’s perspective minimizing the interpretive flexibility of the reader. The slinky was an artifact students used to produce the waves; and therefore, the slinky was the referent of the wavy line. The fact that the artifact was a slinky was lost in its transduction from the artifactual to the diagrammatical mode; instead the waves were foregrounded by the wavy line diagram.

During the post-experiment follow-up lecture the next day (Day 3), during which I summarized the previous day’s experiment, I wanted to emphasize the wavy-line diagram’s value to encourage my students to diagram wave characteristics in future activities. I diagrammed the experimental setup as seen in Fig. 4.2.3 (also reproduced below for reader’s convenience), and explained its features using both speech and the back and forth hand gestures (or BFGs as previously discussed, see Fig. 4.1.7). I reinforced the diagramming practices enacted by the team who drew the wavy-line diagram on their whiteboard (Fig. 4.2.2b) by including a textual label (“View from above”) in the same way they did to provide perspective. My uptake of this diagrammatic feature by using it in my diagram not only provided positive and public feedback to students, but it also assigned value to recognizing perspective when constructing and reading diagrams.

Diagramming was becoming a prominent mode in my class. Since wave diagrams often afford iconic depictions of wave characteristics that I intended for my students to develop, with my diagramming during this lecture, I intended to model appropriate diagramming practices both to assign them cultural value, and to promote students’ linking the wavy-line aspects of the diagram to the wave characteristics (e.g., amplitude) which were anchored in their artifactual engagement with the slinkies. My BFG acted as a multimodal scaffold that mediated the link between the action of creating a wave in the slinky (i.e., moving the hand holding the slinky back and forth) and the diagram I drew for students during this lecture. More specifically, the prominence of my diagram, and my BFG superimposed over it (Fig. 4.1.7), in relation to the students' production of a wave by shaking the slinky back and forth, show the intertwining of these modes in my class, as my students and I negotiated the concepts of amplitude and wave speed. My diagram also reflected other contextual elements (i.e., a hand holding the slinky in two superimposed positions, helical shape of the slinky, two instances with an example of the elapsed time for each, etc.) to help students to better connect the diagram to their experimental context, and their manipulation of artifacts, while also modeling diagrammatical grammar for students to call upon when diagramming during future activities. For example, the labeled arrows I drew in my diagram (Fig.4.2.3) represented one of the quantities students measured during their experiment ("wave height," as indicated by the arrow's label), which was important for students to grasp in order to understand amplitude, which I define later in my diagram shown in Fig. 5.1.3.

While students were measuring wave amplitude, they were not aware of the term amplitude, but had an intuitive sense that a wave possesses the characteristic of height or tallness. In the absence of academic language, students used colloquial speech to talk about this characteristic as they also engaged with it through artifactual, gestural, and diagrammatic modes. The experimental task afforded students the opportunity to produce a numerical value for wave height, and each group's respective methods for measuring wave height came from their intuitive sense of height, which they applied to the waves they produced in the slinky.

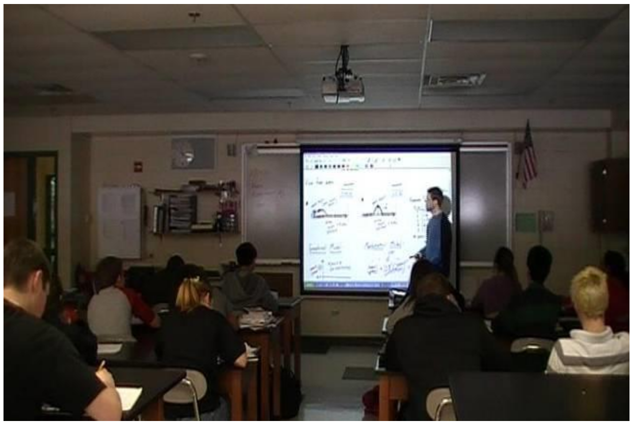
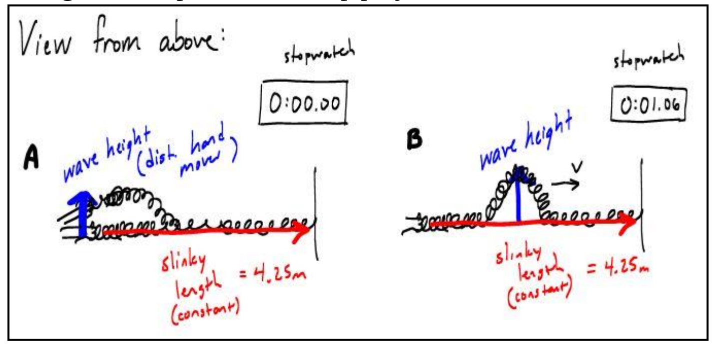


Diagram of experimental setup projected in front of the class:



Reproduction of Figure 4.2.3. (Day 3, 4:00). During the post-experiment lecture, I draw and explain my diagram of the experimental setup for the wave speed vs. height slinky experiment.

Students measured the wave's height in terms of how far their hand moved from its initial position, as was evident from their measurements during the experiment. Although this was not aligned with the scientifically accurate method for measuring amplitude, they correctly measured the distance the hand moved. Instead of measuring with respect to a central axis in the middle of the maxima and minima, which is the scientifically canonical way of measuring amplitude, students measured wave height as the distance between a crest and trough, which would result in a value that was twice the amplitude. I utilized another wavy-line diagram at the end of the lecture to define the scientifically accurate definition of wave height, and introduce it as *amplitude* (see Fig. 5.1.3). I used the diagram to help my students to articulate the meaning of amplitude. The manipulation of the slinky to generate waves with various amplitudes was a referent for the term amplitude, and the wavy line diagram acted as a scaffold linking the term to its referent and to the way in which it was to be measured. My diagram, shown on the right in

Figure 5.1.3, used arrows to represent the distance between two points, which depicted the amplitude's value as the distance between the two specific points displayed in the diagram.

The diagram was the prominent modality used to define amplitude, but was supported by other modes through the textual labels, as well as my speech and deictic gesturing that called attention to the individual points on the diagram, and interval between them (see Fig. 4.1.8), to further explicate the concept of amplitude for my students.

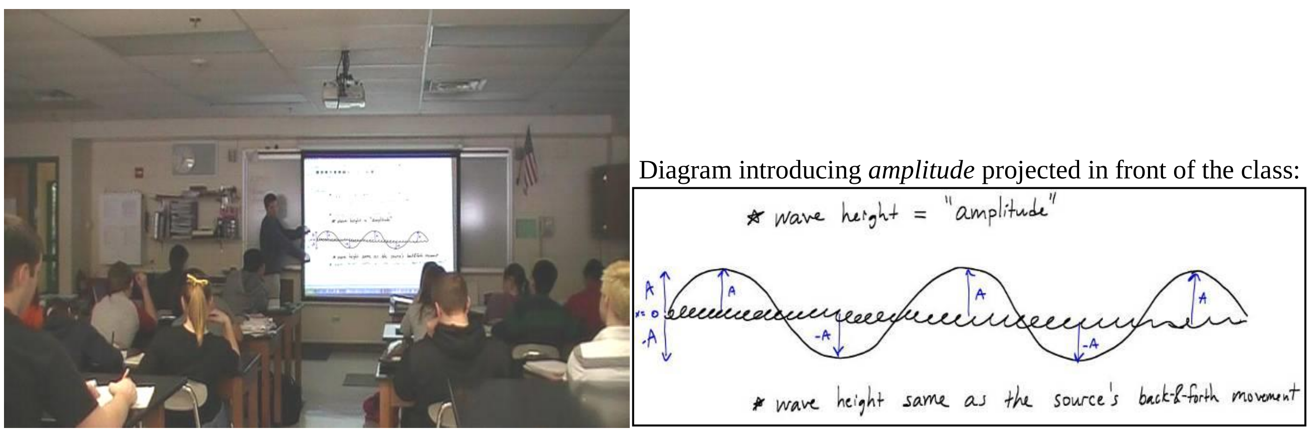


Figure 5.1.3. (Day 3, 18:25). I explain my diagram defining the wave characteristic, *amplitude*.

After my definition of amplitude, a student, Becky, asked about the difference between the width and height of a pulse. Distinguishing these two quantities was critical for students to understand waveform graphs later in the unit. Becky's question introduced a potential limitation of the wavy-line diagram. The diagram is static, but depicts a movement. By *pausing* the slinky wave's motion through the act of diagramming it at a particular instant, a different wave characteristic–wavelength; was afforded as another potential quantity to be measured. Using the diagram, students could measure both the wave's height and length, and, thus, the concept of distance associated with one wave pulse had to become more differentiated (i.e., distance referring to height and distance referring to length). This point of confusion and stimulus for further development did not emerge prior to the diagram, possibly because a wave's length is nearly impossible to measure directly in real-time on a moving wave pulse. Only when the wave was "paused" through the act of diagramming did the possibility of measuring the length of the wave pulse became possible. In addition, the students were not as likely to suggest wavelength as a potential factor affecting a wave's speed that they could test out because they could not directly choose its numerical value, as opposed to the height which they directly manipulated.

Although it appeared that the diagram caused Becky confusion that led to her question, it also provided students with an opportunity to compare and contrast amplitude and wavelength, which could lead to better articulation of these wave characteristics. My response to her confusion was captured in Fig. 5.1.4 as I said, "this [gesture representing the length of the bump seen in Figure 5.1.4a] is different from this [gesture representing the height of the bump seen in Figure 5.1.4b]." Using the wavy-line diagram, I gestured to the spatial interval for width, and then for height, to contrast them. Although the diagram was a primary modality, my gestures called attention to the intervals representing amplitude and the length of one bump (i.e., one-half of the wavelength), which showed students how these quantities were represented on the diagram. Both my gestures represented spatial distances, which communicated that both wavelength and amplitude are such quantities, but they also highlighted that these distances had different orientations, captured by my changing of the gesture orientation from horizontal to vertical as I shifted from signifying the length of one "bump" to signifying the height.

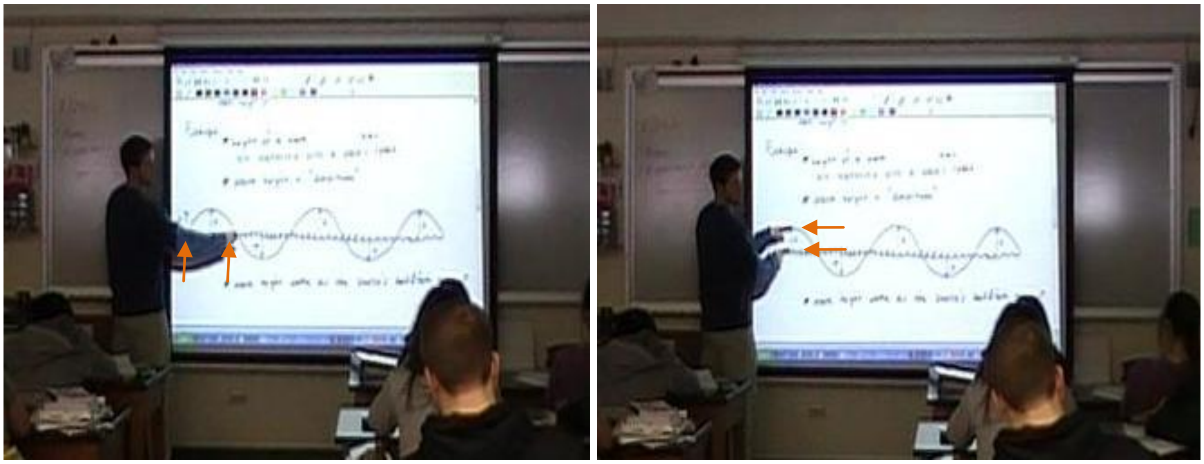


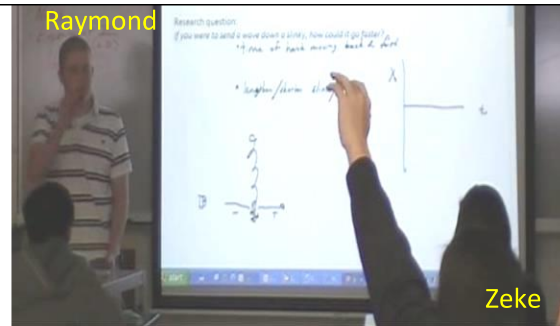
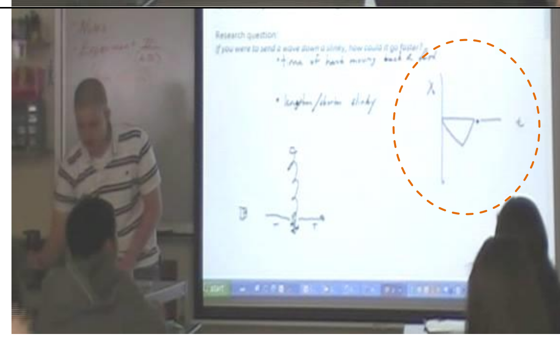
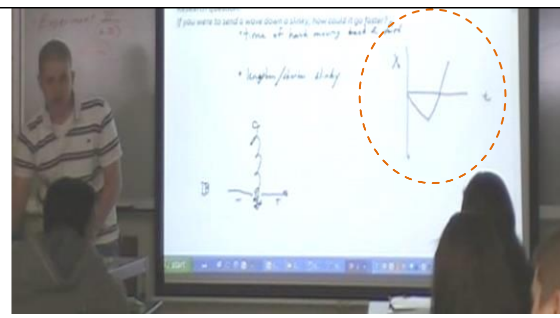
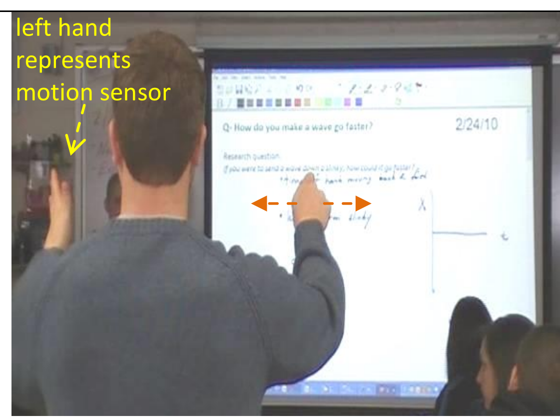
Figure 5.1.4. (a), (Day 3, 19:31). I gesture with my hands to represent the length of a bump. (b), (Day 3, 19:33). I gesture with my hands to represent the amplitude of the wave.

Following the post-experiment summary lecture, I introduced the next two slinky experiments which, although, I had anticipated and planned prior to the start of the unit, they emerged from students' suggestions related to which possible factors might cause a wave to move faster. Aside from the amplitude, which they had already tested, students suggested *hand-quickness* and *slinky-length* that, scientifically, related to the concepts of period or frequency (hand-quickness) and wave medium (slinky-length) respectively.

Before letting my students conduct experiments seeking the relationship each of these quantities had with wave speed, I had them offer their ideas about how to measure hand-quickness. As discussed previously in Section 4.1, students and I articulated hand-quickness as the *time* for their hand to move back and forth while creating a wave using BFGs. The hand-quickness became a referent for the term *period* that students were familiar with from prior units, albeit not in relation to waves.

The modalities students used to describe how to measure the period shifted from speech and iconic hand gestures to diagramming the ways in which they anticipated engaging with the artifacts and their predictions about the computer-generated graph of the motion sensor's data, (which hereafter will be abbreviated to the motion sensor's graph). The shift to diagramming as a primary mode occurred after Raymond suggested using a motion sensor to measure the period. I asked him to come to the front of the class and draw a diagram of the position-time graph he would expect the motion sensor to produce. He immediately drew axes but right away started to struggle to draw any curve. As a scaffolding move, I asked him to diagram the experimental setup (see transcript in Fig. 4.2.4).

His diagram of the experimental setup served as a scaffold for students to negotiate their expectations for the appearance of the motion sensor's position vs. time graph. The public and collective transduction of Raymond's diagram of the setup to a free-hand graphical sketch representing the motion sensor's graph is captured in Figure 5.1.5. As seen in the still photo for Unit 1, Raymond's positioning of the motion sensor in the diagram was well defined, and provided the footing for Raymond and other students on which to base their graphical construction. Although his talk and diagramming of the motion sensor and experimental setup were accurate, he could not predict the motion sensor's position versus time graph. His talk and diagramming demonstrated his understanding of perspective regarding diagrams (i.e., he recognized that he had to draw an above view of his experimental setup), and the function and utility of a motion sensor as a device that collects position and time values of an object in experimental contexts. However, his inability to predict the shape of the motion sensor's position vs. time graph reflected a lack in his understanding of how to transduce to the graphical modality. As previously discussed, Raymond understood the orientation and spatial aspects of a motion sensor (i.e., the motion sensor measures position, and positive direction is away from the sensor while negative is towards the sensor), and the hand’s motion as it created waves, which he depicted in his diagram (shown in Fig. 4.2.4). Raymond became confused when asked to transduce these ideas to the graphical mode, which required an understanding of both the ideas and how to engage with the graphical modality. More specifically, he was not able to shift the spatial positioning of his hand with respect to the motion sensor, which he depicted in the diagram, to the free-hand graph’s axes as a function of time. His public confusion allowed for that the students and I to negotiate and develop this transduction as a class, which is shown in Fig. 5.1.5.

1	Teacher	What's the graph going to look like, and you can call on people too Raymond, then just draw what they say. [*several students raise their hands and Raymond calls on Zeke*]	
2	Zeke	It's going to start out at the x-axis, because it's at the zero position—	
3	Raymond	—yeah [*says in agreement*]	
4	Zeke	and if we move close to the motion sensor then it's gonna be going down, and then if it's moving away from the motion sensor it's going to be going up, and yeah, it'll eventually come back to the x-axis because it's where it started [*Raymond draws the graph as Zeke verbally decribes it. The free-hand graph is denoted by the dotted circle pictured to the right*].	
5	Raymond	Yeah, because it'd be zero and then it'd go back up right? [*Raymond extends the graph past the x-axis as seen in the graph pictured to the right*]	
[*The class begins talking to each other debating the graph's shape, and I have Raymond erase the curve and start over to negotiate its shape from the beginning*].			
6	Teacher	[*ask Raymond to consider first where the plot will begin if the hand starts out in front of the motion sensor*] So here's the motion sensor [*enactment gesture with my left hand*] and you're gonna be moving your hand in front of it as you make waves [*I move my right hand back-and-forth in front of my left hand denoted by the dotted arrows*] So if I'm not moving yet, what's that gonna look like on the graph?	

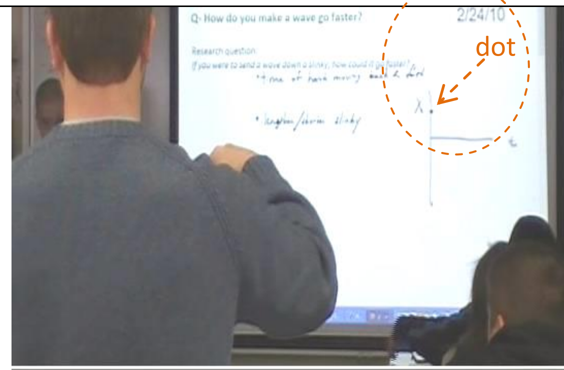
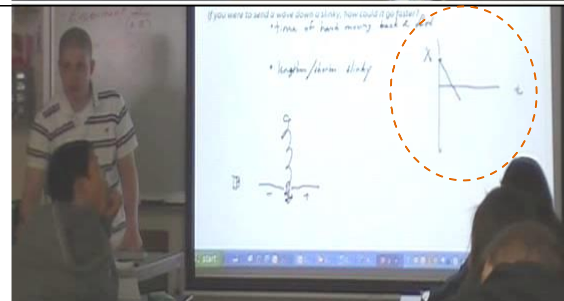
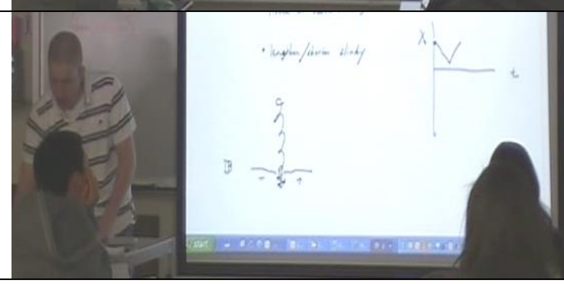
7	Raymond	Wait, so you like have some position [*makes a dot on the y-axis to show his starting point as seen in the picture to the right*] And then [*becomes hesitant and pauses, after several seconds, I call on Katie to help*]	
8	Katie	Won't it drop a little bit [*Raymond draws what is pictured to the right*] Not past zero, it won't hit zero cause it's not gonna be touching the motion sensor	
9	Raymond	Oh yeah, right [*Raymond erases and re-draws the free-hand graph shown to the right*]	

Figure 5.1.5. (Day 3, 25:35-26:10). Raymond draws a free-hand graph based on other students' suggestions. The graph represents students' expectations of a motion sensor's graph of a wave in a slinky produced by one's hand movement.

Based on Raymond's linguistic and diagrammatic description of a possible setup to measure the period of someone's hand that creates a wave in the slinky, Raymond understood how a motion sensor collected data as evidenced by his diagramming its spatial positioning relative to the hand's back-and-forth motion. It was not entirely clear from the transcript in Fig. 5.1.5 how well Raymond was able to reason within the graphical modality; that is, to what extent he could translate between diagrams and graphs. However, he understood that my hand would initially have a nonzero position (Unit 7), which he concluded with the help of my gesturing the relative positions of the motion sensor and hand. My gestures called his and the class' attention back to the positioning of the motion sensor relative to the hand's back-and-forth motion, and prompted him to use this reasoning as he sketched the graph. He struggled to graphically describe the positioning, as indicated by his extending the graph past the x-axis in Unit 8, but was corrected by Katie. Katie's linguistic description of her expectations for the graph, and moreover her ability to correct Raymond as to why he should not extend the graph past the x-axis, indicated her conceptual understanding of how the motion sensor functions (i.e., measures the distance between the an object and the front of the sensor), and her ability to engage with the graphical modality. Both of these were critical to her and other students' conceptual development of waveform graphs and wave characteristics throughout the unit.

At the end of class (Day 4) after conducting the slinky experiment in which they sought to determine period's relationship with wave speed, the groups analyzed their data. Addy's utterance, gesture, and speech reflected her graphical understanding of period as the time for one's hand to make one wave cycle. She also successfully navigated the graphing software and its tools in order to take quantitative measurements to determine the period. As the focal group examined the motion sensor's graph, Addy deictically gestured to the screen as she explained to Kevin how to measure the period (see Fig. 5.1.6). Her explanation incorporated deictic gestures to call out the two points on the graph between which the wave was being created, and whose time difference depicted the period, just as we had done the day before as a class when Raymond sketched students' expectations for the shape of the motion sensor's graph.

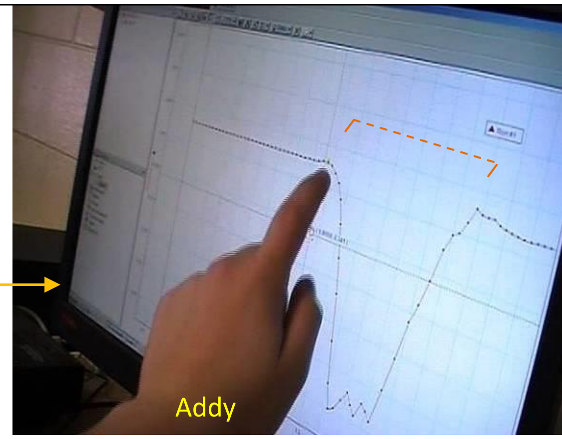
Addy	This is gonna be the period, right? [*Kevin struggles to determine x,y coordinates*] No, you click um that thing [*points to the button on the computer program that displays x,y coordinates at any point on the plot*], and then you put that on that point and find there [*she points at the point on the plot where she wants to find the x,y coordinates*], and then you can find the difference [*she scrolls her hand between the two points denoted by the dotted bracket in the photo to the right. She meant to find the difference in time from when the hand is moved to when it returns*]	

Figure 5.1.6. (Day 3, 45:37). Addy explains to her group how to measure the period from the motion sensor's graph.

Two days later on Day 6, my learning goal was for students to not only differentiate between, but to derive numerical values for the wave characteristics of amplitude, period, and wavelength directly from vertical position vs. time graphs and vertical vs. horizontal position graphs. From these measures, the students were then to calculate the frequency and wave speed. The concepts of wavelength and frequency had not been directly discussed prior to this activity, nor had students explicitly studied waveform graphs in this way.

The activity introducing the waveform graphs to students aimed to utilize transduction between modes. Student engagement began with Mallory publically generating waves in a slinky while a motion sensor captured her hand's position as a function of time (see Fig. 5.1.7). Instead of a diagram of the experimental setup, Zeke took a photograph from above which I later projected in front of the class. For the activity as shown in Fig. 5.1.7, two meter sticks were placed end-to-end on the floor alongside a slinky with which Mallory would make continuous waves that Zeke would photograph from above. While Mallory created the waves, a motion sensor plotted her hand's back and forth movement and generated a real-time position vs. time graph projected in front of the class. I then publically displayed Zeke's photograph and the motion sensor's graph side-by-side (Fig. 5.1.8) on the screen in front of the class. To make the slinky in the photograph appear similar to a waveform graph, I drew in labeled axes, marked off each 10 cm on the meter sticks with dots, and traced a dotted line over the slinky to show where the slinky would be positioned ideally if its amplitude were not diminishing as it propagated. In small groups, students then answered two questions displayed on the screen in front of them (seen at the top of Fig. 5.1.8), and wrote their answers on a small 1x1 ft. whiteboard.

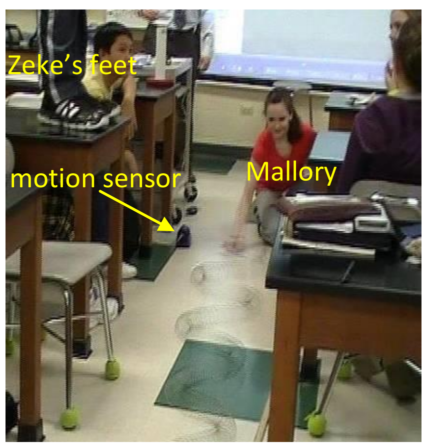


Figure 5.1.7. (Day 6, 5:21). Mallory creates continuous waves in a slinky that Zeke photographs from above, and a motion sensor produces a real-time waveform graph of her hand's back-and-forth movement.

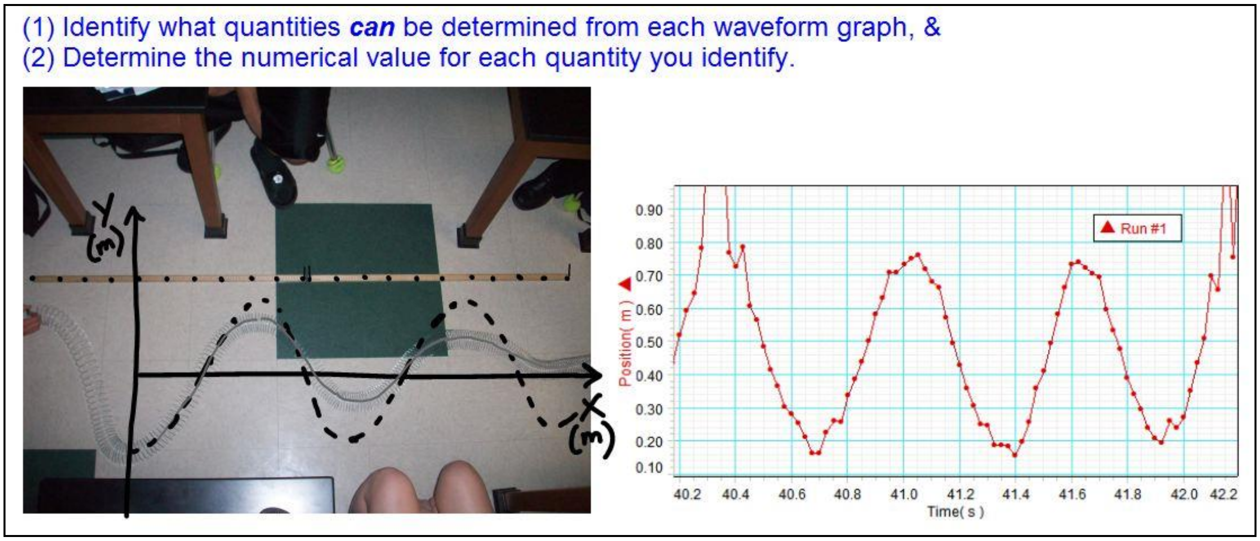


Figure 5.1.8. Waveform-graph lesson. I project Zeke's photograph of the slinky (left) and the motion sensor's graph (right) on the screen in front of the class. The groups were to write answers to the two questions written above (top).

I scaffolded students from seeing the photograph on the left in Figure 5.1.8 as a real-world *image* of the artifacts to seeing it as a wavy-line *graph* (or waveform graph). The photograph was anchored in the students' real-world experience since it was a snapshot of the artifacts and setup they had just observed. To aid students' transduction between the image and graph, I superimposed a wavy line over the slinky to make the wavy aspect of the slinky more pronounced. In order to encourage students to make this transition, I used the diagrammatic modality and their past experiences with wavy lines, such as those seen in Figures 5.1.1 and 5.1.3, to sketch a wavy line on top of the slinky as waves traveled through it. Adding graphical axes shifted the diagram to a waveform graph with horizontal and vertical position axes. The photograph as it is shown in Figure 5.1.8, therefore, acted as a combination of different photographic, diagrammatic, and graphical modes. Photographs are not diagrams, but my superimposed sketchings abbreviated the visual field and added labels, both hallmarks of diagrams. The sketching foregrounded the wavy-line nature of the slinky while backgrounding the visual details captured by the photograph that were not relevant to our activity (e.g., colored tiles on the floor, table legs, students' feet). Furthermore, the addition of the axes provided the diagram-photo combination with graphical features (e.g., axes). The abbreviations of the visual field and the labels that are characteristics of diagrams transformed this representation into an entity similar to the free-hand graph with which students were already familiar. It was my intention to superimpose the wavy line over the photograph to call students' attention to the wavy nature of the slinky and its resemblance to the wavy-line diagrams used in earlier lessons. Then, adding axes encouraged them to further shift into engaging with it as a free-hand graph that was scaled based on the meter-sticks in the photograph. In this way, students could then engage in the graphical modality (i.e., waveform graphs) with the wave characteristics without losing the contextual backdrop provided by the photograph.

As the focal group began identifying wave characteristics they could measure (answering the two questions at the top of Figure 5.1.8), they negotiated the concept of amplitude within the graphical modality. Addy incorrectly mentioned that amplitude was the distance between the highest and lowest points in the graph. There was no debate among the group following Addy's suggestion. Addy's inaccurate conception of amplitude might have reflected her group's earlier understanding of "wave height" based both on their engagement with artifacts as they measured wave height in slinkies by how far their hand moved back-and-forth while creating waves, and on the BFG that represented their hand's motion while producing waves. She was not referring to the refined definition of amplitude that I described using the diagram shown in Figure 5.1.3, where amplitude should be measured with respect to a central axis. It is unclear to which of the two projected graphs (i.e., the one on the left on top of photograph or the one to the right which is the motion sensor's graph in Figure 5.1.8) she was referring, but her mistake may most likely be a result of the motion sensor's position-time graph's lack of a central axis. If I had drawn in a central axis over the position vs. time graph, she might have more readily recognized it as a reference point for measuring amplitude. Addy's mistake illustrated a limitation to motion sensor's graphs, namely that a central axis needs to be envisaged. I anticipated this limitation and tried to use it as a pedagogical strategy to require students to imagine (or draw in whenever possible) a central axis from which to measure the amplitude. It is likely that Addy's difficulty with imagining a central axis led her to the inaccurate conceptualization of amplitude. Prior to this activity, I had always drawn in a central axis for them (as seen in my diagram in Fig. 5.1.3, and the waveform graph on top of the photograph in Fig. 5.1.8).

The act of measuring wave characteristics affords students engagement in a mode that is not foregrounded when they are simply asked to identify them. Had Addy's group attempted to *measure* the amplitude, as it was asked of them when she made the incorrect conceptualization, she may have immediately corrected herself. This was evident moments later when I intervened to remind the group that I not only wanted them to list the wave characteristics, but the numerical values for these characteristics as well. During this exchange, when Addy suggested amplitude as a wave characteristic, I asked her to derive it from the projected graphs and handed her a laser pointer with which she could deictically gesture to the project graphs from her seat as she answered. Although the groups were all working independently at that time, all groups were using the projected graphs, which were the only information provided for this activity. The laser pointer made it possible for Addy to point to locations on the graphs from her seat without walking up to the screen in front of the class. She pointed to where she envisioned the central axis (see photo on the left of Fig. 5.1.9) and the crest (photo on the right of Fig. 5.1.9), while explaining that the distance of “about 0.15 meters” between these two points was the amplitude. By requiring Addy to articulate the meaning of amplitude using a graph in relation to how it is measured, she was able to correct herself and demonstrate her graphical understanding of amplitude. Providing Addy a laser pointer afforded her with an opportunity to deictically gesture to the graph as she explained. Despite her earlier mistake, her explanation here was scientifically correct.

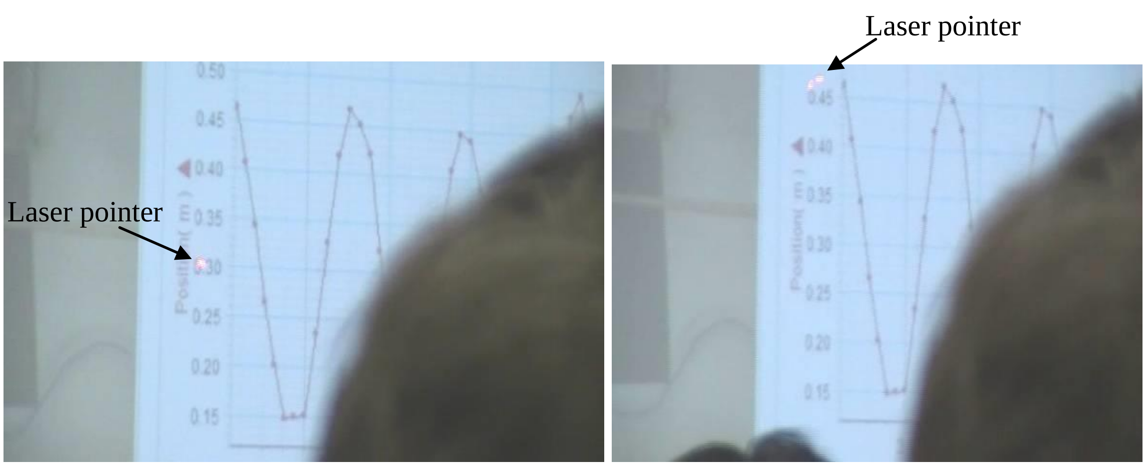


Figure 5.1.9. (Day 6, 11:28-29). Addy gestures to the motion sensor’s graph projected on the screen to explain to her group a method for graphically determining amplitude.

Like the focal group, all of the groups were all able to independently derive amplitude from the motion sensor’s graph. This is significant since prior to this activity, I had not explicitly taught students how to measure wave characteristics from waveform graphs, and it was, therefore, students' first experience engaging with wave characteristics in the graphical modality. The ease of identifying and measuring this particular wave characteristic can be linked to their understanding of the diagram we used earlier to visually define amplitude (Fig. 5.1.3). When I drew this diagram on Day 3, I created a resemblance with the waveform graphs I anticipated us using here on Day 6 to introduce waveform graphs, from which students would measure wave characteristics, such as amplitude. In Fig. 5.1.3, the slinky was drawn with a straight line through the middle of its propagation, or a central axis, which is a graphical feature that could aid students' meaning making of a waveform graph by making it resemble to a diagram.

I also chose to show a continuous train of pulses instead of the single pulse that the students were most familiar with at that time on Day 3. This not only connected the wavy line drawing to the diagram, but also linked the diagram to the waveform graphs that exhibited a wavy or sinusoidal shape. I was using the wavy nature of this diagram on Day 3 (Fig. 5.1.3) as a scaffold for students to make meaning of the waveform graphs during Day 6 (Fig. 5.1.8) in order to promote their conceptual development of wave characteristics as measureable quantities derived from a graph.

The transduction between the diagrammatic and graphical modes was facilitated by the similar and familiar features shared among them. As students engaged with multiple modes, they developed intertwined meanings that were afforded by the various modes. The wavy line was similar in shape to that of a waveform graph from which it was possible to derive all of the following wave characteristics: amplitude, period, wavelength, frequency, and speed. My students and I collectively constructed new meanings as we discussed the waveform graph, in which I used familiar features from modes that had been previously used to mediate their explanations using graphs, such as the BFG previously discussed and seen in Fig. 4.1.10, and an arrow as a diagrammatic label. As Brian identified one complete wave cycle on the graph in front of the class, he talked and pointed to the graph with the laser. I drew an arrow on the graph to illustrate the interval of one complete wave cycle that he described in order to make permanent his deictic use of the laser pointer (see Fig. 5.1.10). My drawing the arrow visually represented the interval Brian was describing as he said, “from here to here, and then here to here,” and deictically gestured with the laser pointer along the curve pausing at successive crests on the graph. The arrow was a diagrammatical feature that I inserted into this graphical mode to facilitate bridging the students’ meaning making within graphs to that within diagrams.

By pointing out successive wave cycles, Brian was demarcating the wavy line into its repetitive cycles. Instead of considering a wavy line as simply representing a wave like he and many students had done on Day 1, Brian was now considering the wavy line as a series of individual wave cycles.

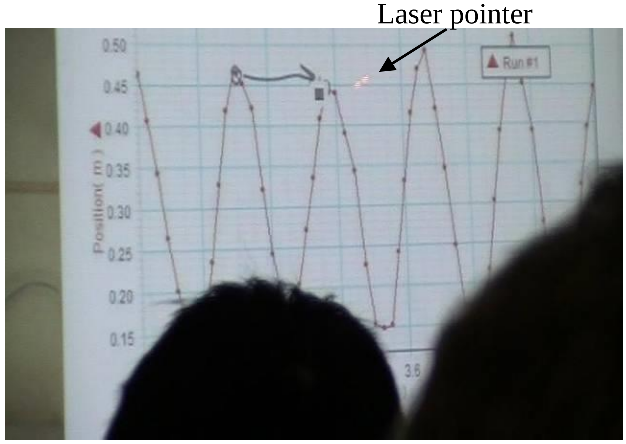


Figure 5.1.10. (Day 6, 17:35). I draw an arrow on the motion sensor’s graph to make permanent the laser pointer’s gestures used to show the interval of one complete wave cycle on the graph.

Demarcating a wavy line into its cycles was a critical step to students' graphical understanding of other wave characteristics such as period and wavelength. After I drew the arrow from crest to crest, Brian immediately suggested that the arrow represented "the time for one wave," or in other words, the period. His saying "time for one wave" instead of the term *period* is significant because he was verbally defining the *concept* of period; he was not simply uttering a scientific term without understanding its referent. His words indicated that he was attaching the numerical value for the time interval to his graphical definition of one wave cycle. Furthermore, his recognition to measure the time for one wave was likely promoted by my drawing the arrow, which was a diagrammatical feature used in the past to depict an interval, which could be found by determining the difference between two points. In this case, the arrow was an epistemological affordance for students that led them to measuring an interval between two points. Since time was plotted on the x-axis in the motion sensor's graph, Brian recognized that the difference would provide a time value, and since the arrow denoted one complete wave cycle, that time would be for one wave.

The notion of measuring an interval between two points that bound one complete wave cycle could also be applied to the graph superimposed on the photograph shown in Fig. 5.1.8, whose x-axis was length (or horizontal position). Oliver recognized this and suggested wavelength as a possible wave characteristic. Oliver first used the laser pointer to trace out one wave cycle, which I depicted in Figure 5.1.11 with a dotted line. After Oliver suggested "wavelength," I asked him to explain what that was, to which he responded, "the width of one cycle from a vertical vs. horizontal position waveform graph." Oliver applied Brian's same measurement technique to the photograph's waveform graph (vertical vs. horizontal position), as opposed to the motion sensor's graph which Brian had used (vertical position vs. time). It is worth noting that wavelength was a characteristic I had not yet formally introduced to the class at that point, except of mentioning it briefly during my exchange with Becky regarding the differentiation between a wave's height and width (Fig. 5.1.3) that was discussed earlier.

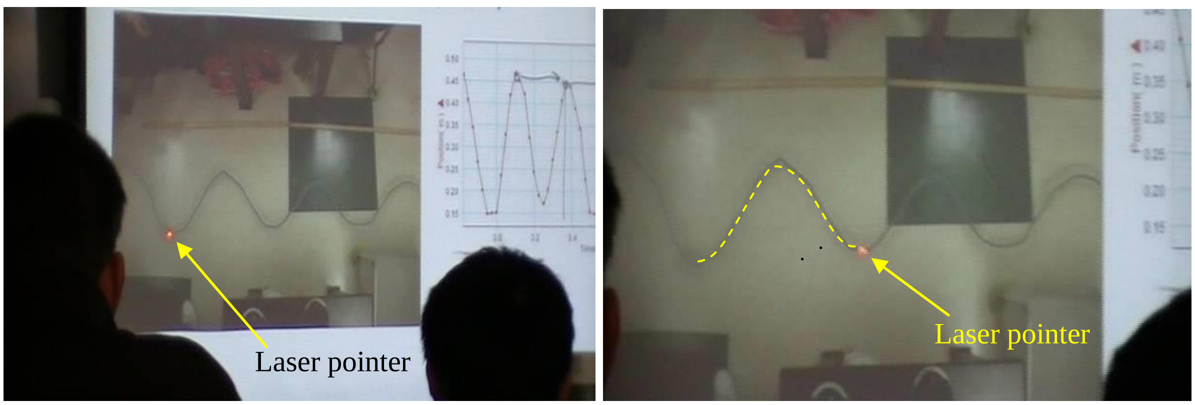


Figure 5.1.11. (Day 6, 18:26-27). Oliver suggests that the wavelength can be measured from the photo's graph using the same technique Brian used to get the period from the motion sensor's graph moments earlier by tracing along the waveform denoted by the dotted line.

As discussed earlier, computer-generated graphs, such as those produced by motion sensors often require students to envisage a central axis, which might limit students' ability to correctly measure amplitude from a graph. However, this might not necessarily hold true for free-hand graphs where there is no computer-generated x-axis. The author has to draw an x-axis as part of the diagramming process, and can therefore choose how to draw it. This was the case when I asked Katie to draw a free-hand graph of the motion sensor's graph on her team's small whiteboard moments before the whole-class discussion, which is shown in Fig. 5.1.12. She drew a central axis on her free-hand graph at a value of 0.3 meters on the y-axis even though there was no central axis on the computer-generated graph.

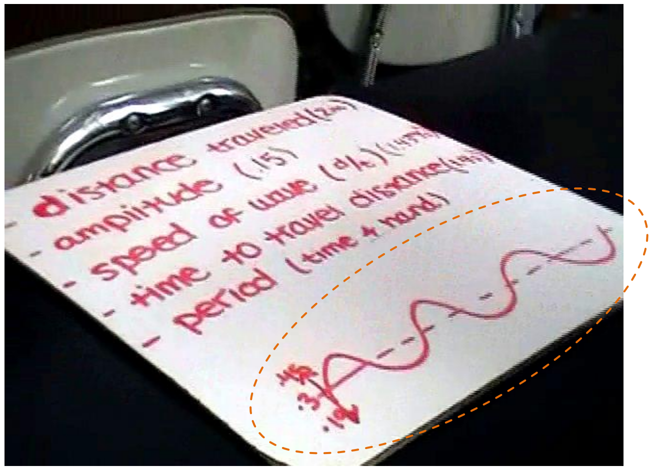


Figure 5.1.12. (Day 6, 13:49). Katie's free-hand graph represents the motion sensor's graph projected on the screen.

Katie demonstrated on several different occasions her understanding of amplitude as a measure from a wave's crest or trough to its central axis, and that a central axis can be drawn onto a graph if it is not already present. During the whole-class discussion as Katie used the laser pointer to help explain how she measured amplitude to the class, she described the central axis she had drawn on the small whiteboard (see Fig. 5.1.12). Her linguistic description to the class was transduced to the graphical mode as I drew in a central axis through the motion sensor's graph while she spoke as seen in Figure 5.1.13. This reinforced Katie's verbal contribution and afforded students a means for deriving amplitude graphically during future activities. Katie again drew in a central axis the next day while solving practice problems in order to measure amplitude (see Fig. 5.1.14).

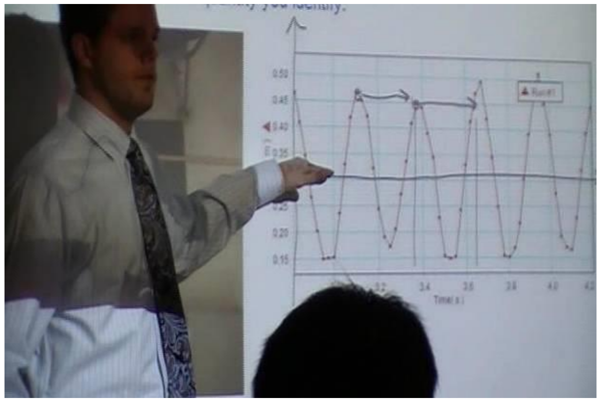


Figure 5.1.13. (Day 6, 20:45). I draw a line on the computer-generated graph to represent a central axis.

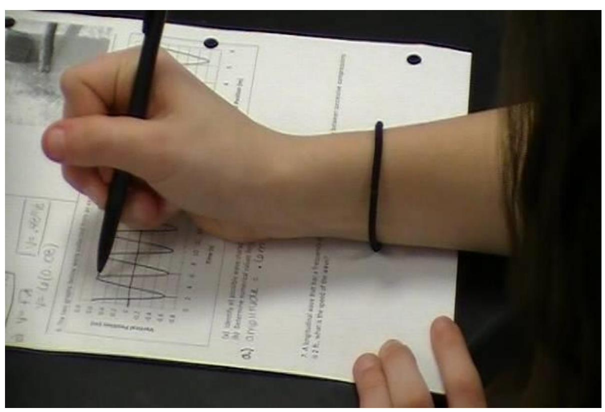


Figure 5.1.14. (Day 7, 35:33). Katie draws a new x-axis on a computer-generated graph before measuring amplitude during a practice problem the next day.

Katie's explanation focused on the motion sensor's graph, as opposed to the photograph's free-hand graph (Fig. 5.1.8). Numerical values are easiest to obtain from a graph when it has a clear quantitative scale, a reason for why my students used the motion sensor's graph to measure amplitude instead of the free-hand graph. I asked the class if they could measure the amplitude using the free-hand graph and they gestured as if they were measuring amplitude on the free-hand graph in the same way Katie had just presented. Zeke then suggested that amplitude was better taken from the motion sensor's graph rather than the photograph's free-hand graph because "the numbers are more accurate." This reasoning was also exhibited by Katie and Addy who also referred to the motion sensor's graph when determining amplitude, and pointed out a major benefit to computer-generated graphs–their quantitative accuracy.

Similar to drawing diagrams, the act of drawing a free-hand graph forced students to foreground certain graphical features they considered important while backgrounding others they did not find as important. Two days later on Day 8 (see Instructional Outline in Appendix), as the focal group prepared their whiteboard, they chose to draw a free-hand graph on the whiteboard representing the computer-generated graphs given in a practice problem. In their free-hand graph, the focal group only labeled particular values on the axes that they used to determine the numerical values of wave characteristics. The focal group's free-hand graph (Fig. 5.1.15) depicted the computer-generated graph I provided to them as part of the practice problem (seen on the left in the Fig. 5.1.16). Once completed, the free-hand graph served as an abbreviated depiction of the computer-generated graph that complemented their class explanation that followed.

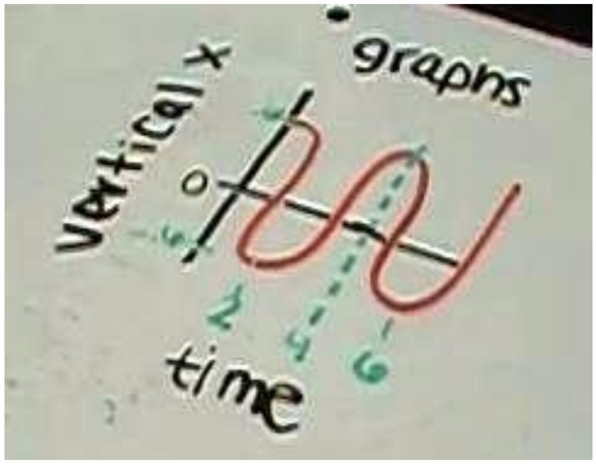


Figure 5.1.15. (end of Day 8). Focal group's free-hand graph on their whiteboard of the computer-generated graph provided in Practice Problem #6.

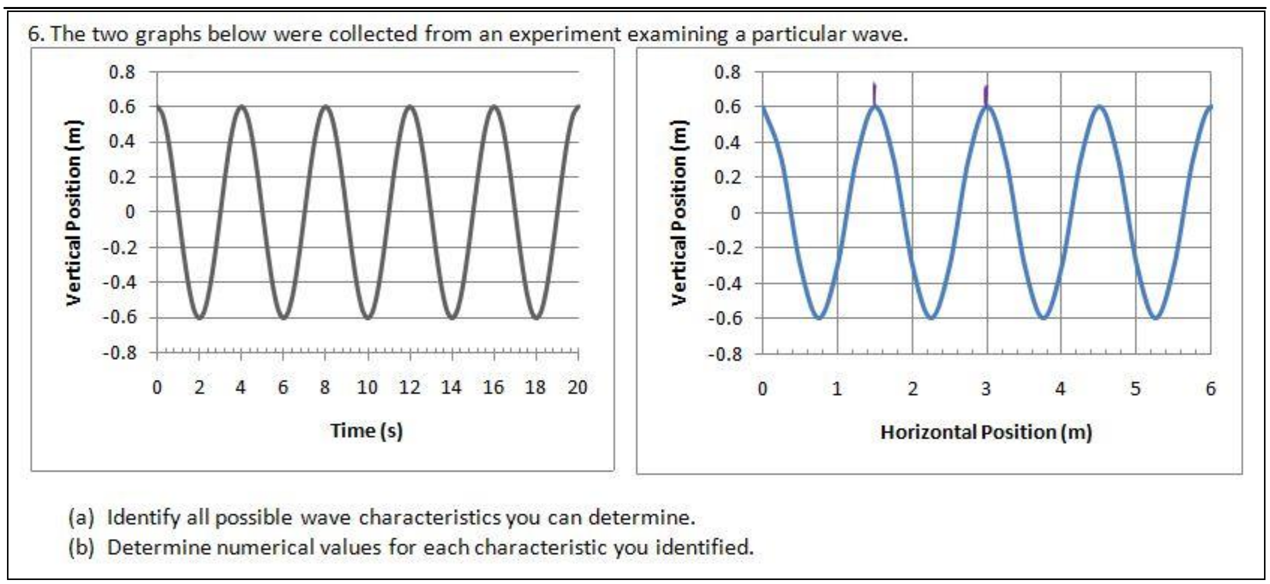


Figure 5.1.16. (Day 8). Practice Problem #6. The focal group was assigned to write out the solutions to this problem on a whiteboard.

The students in the focal group further shaped their understanding of wave characteristics through the free-hand graphs as they were interwoven with speech, gestures, graphs, and diagrams. The students' free-hand graphs revealed both their individual and their collective understandings as they worked together as a group and negotiated their accurate free-hand graph. Although Katie drew the vertical position versus time free-hand graph (y-t graph) seen in Fig. 5.1.17, the group was discussing what she was drawing, thus making Katie's graph a product of the entire focal group's collective work. They labeled the 0.6 and -0.6 values on the y-axis that corresponded to the crests and troughs, respectively, to aid their reasoning regarding measuring the amplitude. On the time axis (x-axis), they chose to label only those numerical values at the crests and troughs. It should be noted that although the dotted line at t = 4 sec could be interpreted as the end of the first cycle in the graph, reviewing the video recording offered evidence that the students were simply linking the time value of 4 sec with the point on the graph (i.e., the crest) to which it corresponded (see Fig. 5.1.17). This was also evident after considering the second graph (Fig 5.1.18), which did not include a green dotted line since it was not necessary as the x-axis values were written next to the corresponding points on the graph. Therefore, the dotted line was not intended to denote the end of the first wave cycle; it was simply a coincidence that it was located at this point.

Although students did not use arrows to denote the distance between crests, they made linguistic and gestural interpretations and justifications of the features of their whiteboard's free-hand graphs as they created them. Addy deictically gestured to seek confirmation from Katie and Kevin that the interval to which she gestured represented the wavelength (see Fig. 5.1.18). Her gesture acted similarly to the brackets and arrows that depicted such intervals on diagrams, and demonstrated that she understood how wavelength should be measured.

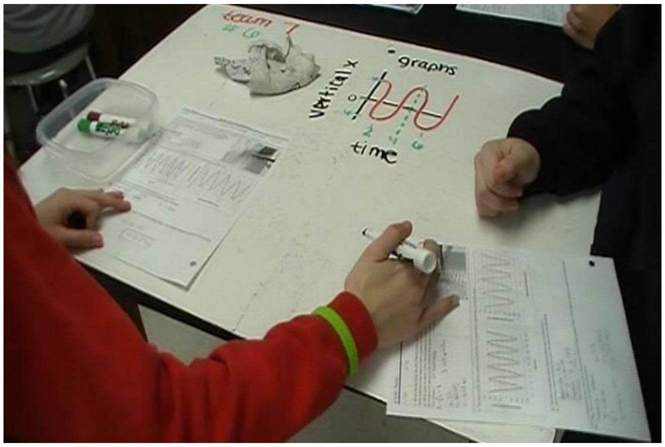


*Figure 5.1.17***.** (Day 8, 1:54). Addy draws a graphical sketch of the *y*-*t* graph from problem #6.

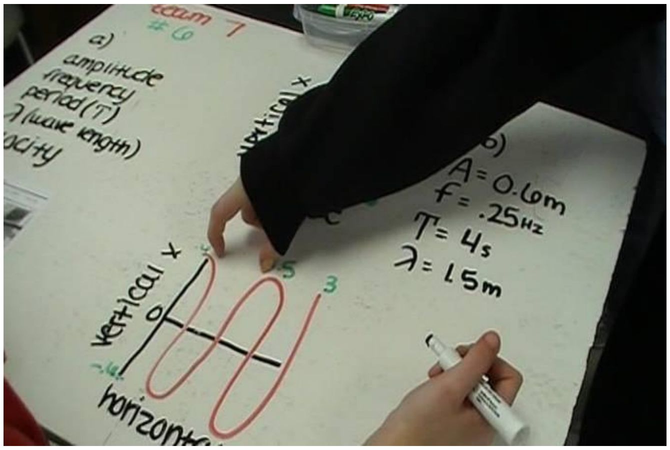
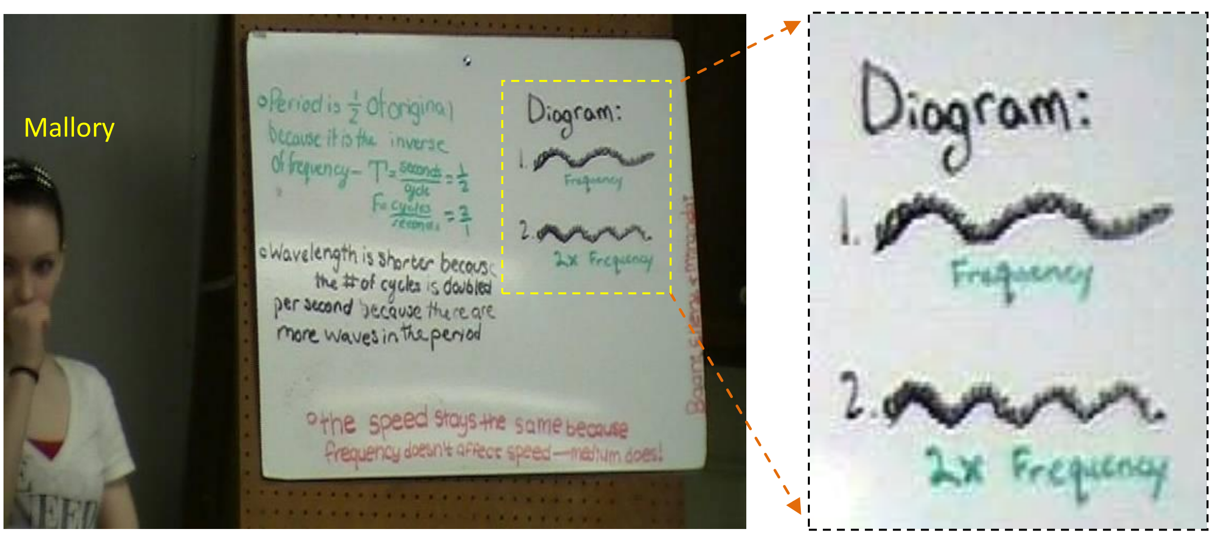
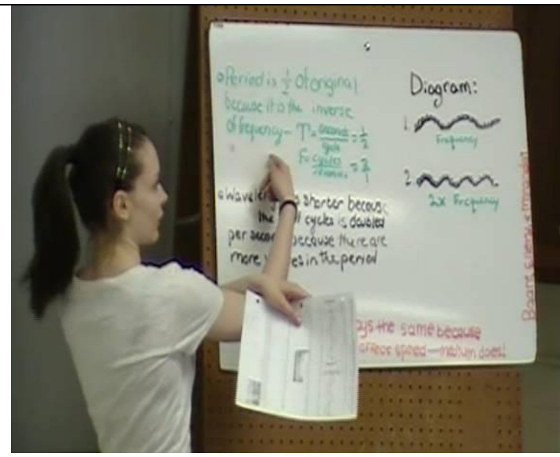
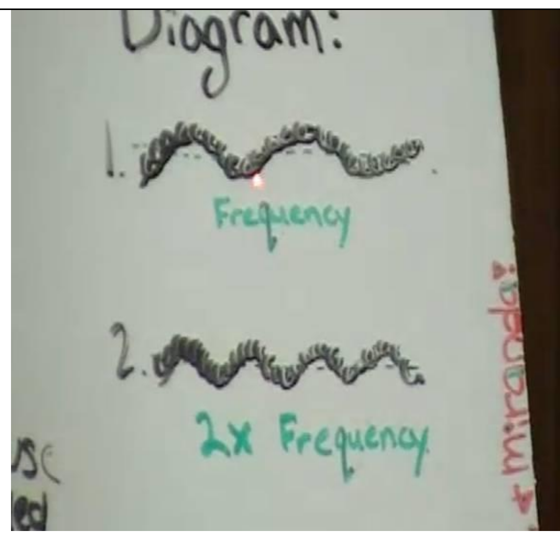


Figure 5.1.18. (Day 8, 5:17)**.** Addy makes interval gesture to represent one wavelength on the *y*-*x* graph**.**

After the groups prepared their whiteboards outlining the solutions to their respective practice problem, one student from each group was randomly selected to present their whiteboard to the class. One group (Mallory and Megan) called upon the diagrammatic modality in addition to written text to answer their question. Mallory represented her group and explained her team’s whiteboard of solutions to Problem #3, which asked, “What happens to the period, wavelength, and speed of a wave on a taut string when the frequency is doubled? ***Explain.***” Her group’s whiteboard is shown in Fig. 4.2.11 reproduced below too for reader’s convenience. Mallory and her group chose to use a wavy-line diagram in their explanation. Mallory did not explicitly describe the diagram in her explanation of the solution, which is shown in Unit 1 of the multimodal transcript in Figure 5.1.19. However, during her presentation she referred to the board mostly without looking at it. She only gestured to the board once when she was describing the reciprocal relationship between period and frequency in which she called upon the units to anchor her reasoning and justify her answer. When I asked Megan to point out one wave cycle on the diagram, her ability to distinguish wave cycles on the diagram in Units 3, 5, and 7 evidenced her understanding of wave cycles within both the diagrammatic and graphical modalities where wave cycles are denoted in similar ways.



Reproduction of Figure 4.2.11. (Day 8, 24:20). Mallory (Group 3) uses her group’s whiteboard to explain their solutions to practice problem #3: “What happens to the period, wavelength, and speed of a wave on a taut string when the frequency is doubled? ***Explain.***”

<table>
<tr><td>1</td><td>Mallory</td><td>Our question was “what happens to the period, wavelength, and speed of a wave on a taut string when the frequency is doubled?” [reads off the paper]
So the frequency, if you double it, that means one, the speed of the actual wave stays the same because it’s a constant and everything, and it doesn’t affect the speed, only the medium does, so speed’ll stay the same.
Two, the period, the period is gonna be one half, because kinda what we said before um the period is the reciprocal of the frequency, so it’d be exactly one half of the original one, kinda like we said here, [points to the whiteboard as pictured to the right]
the tau [period] is seconds over cycles and the frequency is cycles over seconds so it’s exactly one half. And then third, the wavelength is going to be shorter because since he period is one half that means the wavelength is going to be longer</td><td></td></tr>
<tr><td></td><td></td><td>[I revoice Mallory’s points for 4 minutes]</td><td></td></tr>
<tr><td>2</td><td>Teacher</td><td>Show us one cycle, Megan [I hand Megan a laser pointer. Megan is in Mallory’s group]</td><td rowspan="2">
</td></tr>
<tr><td>3</td><td>Megan</td><td>From there [Megan points a laser pointer to the left side of the wave #1]
to there. [Megan points a laser pointer to the next trough as pictured to the right]</td></tr>
<tr><td>4</td><td>Teacher</td><td>Right, and now it’s about to go up again, everyone see that? So there’ two cycles. Now show me one cycle on the bottom one, number two.</td><td></td></tr>
</table>

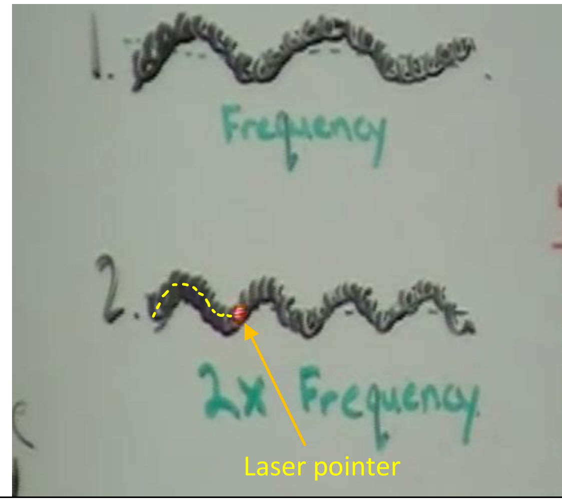
5	Megan	From there to there. [*Megan traces with the laser pointer along the diagram from the left side to the point shown in the picture to the right. A dotted line has been added to the picture to show the path Megan traces.*]	
6	Teacher	Perfect, so how many waves are [shown] on the bottom?	
7	Megan	Four.	

Figure 5.1.19. (Day 8, 23:58-32:36) Mallory and Megan explain their solutions to Problem #3.

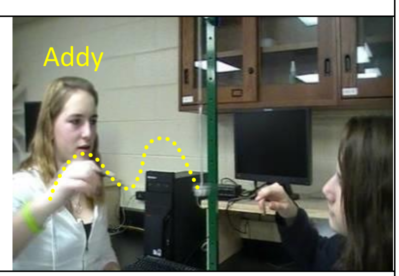
Mallory's correct articulation of ideas across modes presented on her board provided evidence of her understanding of the concepts of speed, period, frequency and wavelength, as well as how these concepts are related to one another. In this case, she was able provide a scientifically accurate explanation of not only how but why other wave characteristics were affected by increasing the frequency. In addition, the fact that she and Megan, as a group of two, had drawn the diagram together suggests that it was a collective product based on their collective understanding of its underlying concepts. The whiteboard may also be considered a collective piece because although the board and diagram was in Mallory's handwriting, Megan was able to correctly interpret the diagram with regards to demarcating one wave cycle within both wavy-line diagrams she and Mallory drew, as seen in Units 2-7 of the transcript in Figure 5.1.19. Their diagram (Fig. 4.2.11) was an original idea that emerged from Mallory and Megan and not a copy of any previous diagram I had provided to students. However, it resembled the wavy-line diagrams my students and I had been using consistently since the first day of the unit. Examining the diagram's features revealed Mallory and Megan's collective understanding that was reinforced by the speech and gesture about it.

The vertical positioning of the two waves as well as their identical horizontal length was significant to demonstrating the students' understanding. The vertical alignment of the two wave diagrams showed that the waves had the same horizontal length, which they did to portray the concept of frequency. They diagram's four wave cycles in the bottom slinky, which had double the frequency (i.e., "2x frequency") fit into the same horizontal space as the two cycles in the top slinky. The students' conceptual understanding of the relationship between frequency and wavelength was also demonstrated by this diagram because of the horizontal shrinking the waves must exhibit in order to double the cycles within the same horizontal space. The spatial aspect of this diagram made it a beneficial mode to in which to think about and communicate these relationships. Mallory and Megan's ability to recognize and call upon, as well as correctly use, the diagrammatic modality was intertwined with their strong collective conceptual understanding.

By the last day of the unit (Day 12), the students in the focal group were choosing to call upon multiple modalities as they engaged with each other about wave characteristics. Moreover, they were using different modes to envisage dimensions of waves that could not be directly observed, such as their use of gestures to *draw* a wavy line in the air that embodied a wave's sinusoidal propagation through air. During Day 12, the focal group, like all other groups, had to figure out the frequency, period, and amplitude of an oscillating mass (see Instructional Outline in Appendix). Since the mass oscillated in air, the propagational or macro-aspect could not be seen, but only imagined. Students in the focal group immediately made undulating hand gestures as if they were drawing wavy lines to envisage a wave propagating through an imagined medium away from the source (see Fig. 5.1.20). This wavy-line drawing in the air was enacted several times, and eventually by every group member, as they negotiated which wave characteristics could be measured and how. The dotted lines in Figure 5.1.20 show the wavy lines Katie and Addy drew in the air that were synchronized with the mass as it bobbed up and down.

Figure 5.1.20. (Day 12, 00:13 & 00:23). Katie (left) draws a wavy-line in the air to show how she imagines the propagation of a wave through an imagined medium if the bobbing mass were the wave source. Addy (right) makes a similar gesture seconds later.

As the multimodal transcript in Figure 4.1.17, which is partially reproduced below in Figure 5.1.21 shows, Addy recognized that there was no wave (Unit 1), which meant that she did not observe any propagation. Katie's suggestion (Unit 2) that there would be propagation if something were attached to the bobbing mass was supported by her undulating hand gesture. With her speech and gesture, she was imagining the diagrammatic modality and attempting to convey it to Addy and Kevin. She drew in the air as her gestures connected her imagined wavy line with the bobbing mass as its source. If Katie were to diagram this on paper, it may have taken more time and it may have lost the contextual elements provided by the bobbing mass as an artifact. She instead elected to enact the wavy line using the undulating hand gesture (UHG) in relation to the actual bobbing mass, as if to reference a diagram that she was imagining and wanted her team to see. Katie, Addy and Kevin all gestured in this way at various points in this activity indicating a collective use and understanding of its function. Their ability to imagine propagation and articulate what they envisaged about the waves that might be created by the bobbing mass as a wave source demonstrated a strong and collective conceptual understanding of wave characteristics.

1	Addy:	Alright, well like how do we like measure period and stuff if there's no waves? [*Addy puts the mass into a bobbing motion by pulling down on it*]	
2	Katie:	Well, because it's going up and down, and if you attach something here [*points to the bobbing mass, and her hand bobs up and down with the mass*] it'd be going like that [*see picture, her speech pauses as she traces the dotted sinusoidal line path shown in the figure. Her hand's up-and-down motion is synchronized with the bobbing motion of the mass on a spring*] and this the source [*points to the bobbing mass*]	
3	Addy:	So we can't like measure anything though, right?	
4	Katie:	Yeah you can	
5	Addy:	You can get the period [*see picture, as she speaks she moves her hand tracing out the dotted sinusoidal line shown in the figure. Her hand's up-and-down motion is synchronized with the bobbing motion of the mass on a spring.*]	
6	Katie:	You can get the period as the time it takes to go one	

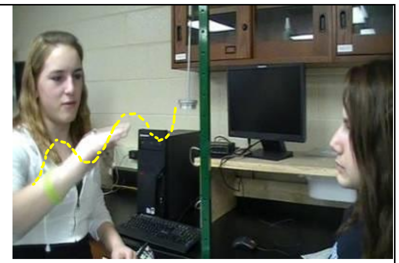
7	Addy:	Cuz we can't like see a wave [*see picture, her flat palmed hand gesture traces out the dotted sinusoidal line shown in the figure*] so how do we know, how can we time it to get from like point A to point B?	
8	Kevin:	Well,= ya know we can= calculate the amount of time it takes to go back and forth so we can get the frequency	

Figure 5.1.21. (Day 12, 00:05-00:30). The focal group negotiates which wave characteristics they can measure from the vertically-bobbing mass.

Summary

This section's findings can be summarized into three ideas regarding multimodality and the teaching and learning of wave characteristics: (1) Different modalities offered different opportunities for concept development; (2) transduction and combination of modalities offered new and various opportunities for meaning making; and (3) increased understanding shaped students' engagement with different modalities.

As students began learning about waves on Day 1, their scientific language to define and talk about waves was limited. During this time, students favored colloquial language, as well as other non-linguistic modalities including gestures and diagrams. My asking students to draw a wave afforded them the opportunity to begin to diagram a wave, including some of its characteristics, which promoted transduction among linguistic and diagrammatical modes mediated by iconic gestures such as the UHG. The diagrams that students created embodied students' past experiences with waves, including water waves, which they commonly cited. The prominence of diagrams during this part of the activity allowed the linguistic modality to support diagramming instead of taking its place. The diagrams offered students an opportunity to articulate their conceptions of waves that was different from the opportunity they would have had via linguistic modes alone.

This lesson's diagramming also promoted the use of diagrams as an effective modality that students and I could call upon during future activities, and afforded the concept of perspective that helped students to differentiate between the macro and micro aspects of waves. Diagramming also provided epistemological affordances for students to examine the shape of the wavy line, which would be later linked to the back and forth motion of waves using the BFG and artifacts, such as the long metal slinky, and then transduced to the graphical modality. The transduction of the wavy line across modes incorporated wave characteristic ideas as students and I made meaning of it.

There was minimal use of diagramming by my students at first. I kept valuing diagramming as a cultural practice in my classroom, and modeled appropriate ways of enacting it (i.e, my suggestions for the diagrammatical grammar), to encourage students to appropriately call upon diagramming during future activities. During my follow-up lecture to the first slinky experiment on Day 2, I utilized a diagram to define a wave's amplitude, and used linguistic and gestural modes to further explicate it. The diagram contained diagrammatical features such as arrows that allowed for the definition of amplitude to be operational by demonstrating how it would be measured. This also shaped the meaning of the wavy line that many students generated on the first day, enhancing it to signify to assign the amplitude of a wave as the height of the wavy line.

The static nature of diagrams afforded opportunities for us to consider motional aspects of waves that could not be easily captured in real-time. Becky's confusion about a wave's height versus its length arose when viewing the diagram I had used to define amplitude. During the experiment in which students measured the wave height, it was not possible to measure length as the wave pulse was constantly moving down the slinky. However, when the wave pulses were "paused" in the diagram, Becky was able to consider this characteristic as a measurable quantity which she sought to contrast with amplitude. In my response, I called upon gestures to represent intervals between two points on my diagram to facilitate students' identification of the length and then the height of a bump. The form similarity of these two intervals captured the similarity of the two quantities, whereas the difference in orientation (i.e., horizontal versus vertical), contrasted them, differentiating them into two distinct quantities of which only amplitude could be measured in real time.

On Day 2, transduction between modes helped students develop the concept of period. The idea emerged spontaneously from students as "hand-quickness," and included a brisk BFG as a referent. Although ambiguous since it could refer to speed or time duration of hand's movement, the BFG supported students' development of the concept as a measurable quantity. Transduction to the graphical mode was afforded by Raymond's diagramming his idea for an experimental setup that utilized a motion sensor to graph the hand's motion, from which the period could be derived. Students and I were able to discuss ideas regarding an experimental setup that did not yet exist because of Raymond's diagram. Students' expectations for the motion sensor's graph were drawn and redrawn as a free-hand graph as we negotiated it together in relation to the positioning of the hand and motion sensor in Raymond's diagram.

Diagramming enabled the position of the motion sensor to become well defined for the students, and suggested a possible anchor for students to base their predictions about what the motion sensor's position vs. time graph might look like. The classroom discourse around Raymond's diagram indicated that Raymond understood how motion sensors, and their spatial positions, functioned in experiments, but that he was limited in his ability to shift from his diagram to the graphical modality. By publically promoting this transduction, students and I were collectively able to conceptualize the period in the graphical modality.

As students then conducted experiments in which they measured the relationship between a wave's period and its propagational speed, they were afforded the opportunity to enact their understanding of period. Addy demonstrated her understanding of period by explaining to her group how it was to be measured from their motion sensor's graph. She incorporated deictic gestures regarding the computer-generated graph by pointing to the points on the graph that marked the beginning and end of the hand's motion as it created a wave pulse, while talking about the difference in time between those points.

Transduction among modes was also critical to students' learning to derive numerical values for wave characteristics from waveform graphs. When students were first introduced to waveform graphs on Day 6, two variations surfaced. In one variation, an above-view photograph of a slinky, while continuous waves were traveling through it, was taken and then projected in front of the class. I transformed the photograph into a graph by drawing axes over it such that the slinky was the line, and the x-axis was the central axis. This graph represented a combination of three modes–photograph, diagram, and graph. Such combinations reflect the blending of two or more modes, but each mode can still function as a separate mode and maintains its own grammar. However, it allows for the intertwining of various meanings that are afforded by the various modes that co-exist in it. The photograph was abbreviated to foreground certain carefully chosen features while sending the rest into the background, which is a hallmark of diagramming. Additionally, features and labels drawn (i.e., axes, scale, and curve) were graphical in nature. Multimodal combinations afford linkages of ideas across modalities. Instead of asking students to simply shift from the primary modality in which they were engaging (like in Raymond's case when he was asked to shift to the graphical mode), this activity utilized a combination of modes. Familiar diagrams and artifacts captured by the photograph were intertwined with graphs with which students were engaging for the first time. Since the curve on the graph resembled the wavy line the students recognized from past lessons, students were supported in linking what they understood about the wavy line diagram (e.g., amplitude and period) to the graphical mode that now provided scale and numerical information.

The other variation of a waveform graph used during this lesson was the motion sensor's graph capturing the hand's motion as it produced waves in the slinky. This graph was generated by a computer, and thus, did not require any features to be drawn. The shape of its line was also a wavy line, and, similar to the first variation, it promoted students' extension of meaning related to the wavy line to that of the curve in this graph.

As Addy and Katie applied the concept of amplitude to the motion sensor's graph, they needed to envisage a central axis from which to measure it. This presented a limitation of computer-generated graphs whose x-axis may not always be the central axis in a waveform graph. This limitation was overcome when students began to draw in a central axis when there was not one already provided, which suggested that a benefit of free-hand graphs is that students have to draw the axes and can choose to draw the x-axis as a central axis when constructing the graph. Drawing in a central axis emerged as a technique to facilitate the measurement of amplitude. Computer-generated graphs and free-hand graphs have both benefits and limitations. Computer-generated graphs' benefits include numerical accuracy from the scale) and limitations include lack of a central axis that must be envisaged, whereas the opposite is true for free-hand graphs.

The act of measuring wave characteristics offered students the opportunity to engage with multiple modes, which promoted the further articulation of their ideas. It was in the context of the act of measuring amplitude that the need for a central axis arouse, which was originally overlooked by the focal group as they identified wave characteristics to measure. Moreover, Addy incorrectly stated how to measure amplitude at first, only to correct herself when she actually took the measurement, and envisaged a central axis by gesturing with a laser pointer as if she were drawing the central axis onto the motion sensor's graph projected in front of the class.

As it was the case with the combination of modes, which was noted earlier, new meaning was built from previous meanings, as modes did not remain independent and isolated, but were rather interwoven and linked through the concepts with which students engaged. I used an arrow (as a diagrammatical feature depicting an interval) to demarcate one wave cycle on a graph as students first engaged with waveform graphs. My arrows were enacting Brian's explanation, and promoted the act of measuring an interval, thus offering students an epistemological affordance to connect period and wavelength in relation to both waveform graphs since they were measured in the same manner (i.e., difference between the beginning and end of one wave cycle along the x-axis). This also imbued with further meaning the wavy line diagram from the first day, including more than height as a wave characteristic as wave's period and wavelength were added.

Students developed different meanings while engaging with a wavy line within the graphical versus the diagrammatical modality. A major benefit of the graphical modality was its quantitative accuracy. Within the graphical modality, the axes afforded the opportunity to engage with quantitative aspects of the wavy line, such as in the motion sensor's graph shown in Figure 5.1.8. The numerical axes of graphs allow for various wave characteristics to be quantified. Diagrams and free-hand graphs can include quantitative information, such as those created by the focal group in Figures 5.1.17 and 5.1.18. In diagrams, the quantitative information is provided to the reader via a labeled vector. However, diagrams and free-hand graphs are not typically accurate for taking numerical measurements since they lack the scale provided by computer-generated graphs.

The process of creating free-hand graphs afforded students in my class, who authored these graphs, the opportunity to label them with particular numerical values derived from a scale graph (i.e., the computer-generated graph) that functioned to justify how various wave characteristic values were obtained. Subsequently, the readers' engagement with free-hand graphs was to interpret the labeled values on the axes in relation to wave characteristics. Computer-generated graphs (e.g., Fig. 5.1.16) provided quantitative information through the scale axes on which the wavy-line was plotted. The numerical values for wave characteristics were obtained by *applying* the concept of amplitude, period, and wavelength to the graph's wavy-line (e.g., amplitude was determined by measuring the distance between the crest or trough and a central axis). The free-hand graphs created by the focal group (Fig. 5.1.17 & Fig. 5.1.18) foregrounded the values on the scale that were used to determine the wave characteristics' values, which explicated and justified these values for the reader. The computer-generated graph possessed more quantitative detail and scale, but students needed a conceptual understanding of the wave characteristics in order to derive numerical values for them. On the other hand, free-hand graphs represented the wave characteristics more clearly by eliminating the milieu of quantitative information and including only those values necessary for obtaining values for wave characteristics. Qualitative labels similar to features typically used in diagramming (e.g., arrows, brackets, written labels) were used to visually define wave characteristics (Fig. 5.1.3), and helped students develop the skills needed to engage with these concepts within the graphical modality.

In generating free-hand graphs, which were interwoven with students' speech, gestures, graphs, and diagrams, the students in the focal group further shaped their understanding of wave characteristics. The transduction from the computer-generated graph in Figure 5.1.16 to the free-hand graphs in Figures 5.1.17-18 offered students an opportunity to re-create ideas from one modality to another. Moreover, in doing so within a group context, the process became dialogic and a collective effort of the group; students expressed what they knew via multiple representations, and their ideas took on new meanings within new modalities. The computer-generated and free-hand graphs can both be considered graphical; however, since they have different *grammar*, or rules and norms for how they are structured, created, and interpreted, they do not constitute the exact same modality. The similarities that these two modalities share, though, facilitated the students' focus on, and developing understandings of, the underlying wave characteristics concepts.

Ultimately, students' facility in engaging with ideas within and across many modes indicates their conceptual understanding. Mallory and Megan chose to use a diagram with text in their explanation of a practice problem (Fig. 4.2.11), which demonstrated their understanding of both the ideas and the modalities they called upon to describe these ideas, as well as the value of diagramming as a modality that they had constructed. Moreover, the focal group called upon multiple modes as they engaged at the end of the unit with a new context–mass bobbing on a spring. Their ability to call upon whichever mode they considered appropriate allowed them to represent for one another aspects of the wave that were not directly observable, such as its propagation through air.

Different modalities students used to engage with ideas ebbed and flowed, but they were also interwoven. Use of each mode did not necessarily contribute distinct meaning to an overall concept or idea, but offered unique opportunities for student engagement and concept development. Transduction between modes, which was mediated by similar semiotic resources and grammatical features shared by the modes, bridged and scaffolded students' ideas. As concepts related to wave characteristics were being developed within different modes, meanings developed within modes previously used were in turn extended, as was the case with the wavy line that transformed from a depiction of water waves to complex waveform graphs of two variations from which quantitative information about various wave characteristics could be derived. The interweaving of modalities, which students called upon and used as they engaged with, and developed, ideas, shaped their overall conceptual understanding and ability to engage with one another using those modes. As students developed conceptual understandings within and across different modalities, the ways in which they engaged with the modes changed too. The changes to the collective diagrammatical practices of my class in turn shaped the concept development within a given mode or modes, forming a reciprocal relationship between the development of concepts and the grammar of the modalities used to represent and these concepts.

Relationships Between Wave Characteristics Determined from Experimental Data

Students investigated waves by measuring and changing pertinent variables (independent and dependent) in order to construct relationships among these variables via experimentation. Although the specific variables and the context of experimentation changed from lesson to lesson, students followed the same general rules: they set up their experiments in a group of the same three students, collected data in their group, and summarized their findings as a group on a 2 x 3 ft. whiteboard. On their whiteboards, each group drew a free-hand line graph of their data and subsequently the equation of the relationship using the graph's regression. In this section, I present ways in which multimodality was part of the students' construction of these relationships.

Constructing Relationships in Multiple Modes

Students conducted three experiments that all utilized long metal slinkies during the unit on waves. The first experiment was to study the relationship between a wave's propagational speed and its wave height (or *amplitude*). The second was to study the relationship between a wave's propagational speed and its period (related to *frequency*). Finally, the third one was to study a wave's propagational speed and the length of the slinky. All of these occurred between days 2-4 of the 12-day unit (see Instructional Outline in Appendix).

These experiments did not have an accompanying handout such as a lab handout, and the groups had to decide how to conduct an experiment and organize the data. My students and I, and the focal group in particular, often used data tables throughout these experiments to organize and analyze data. As students collected measurements of independent and dependent variables, they often organized these data into tables as the values were collected. During the first experiment (Day 2), Katie created waves in a slinky by moving her hand back and forth while Kevin held the other side and Addy recorded their data as they proceeded (Fig. 5.2.1). Katie suggested Addy organize their data into a table. As shown in Figure 5.2.1, Katie made a gesture as she suggested that Addy make a two-column table to organize the independent variable (wave height) and the dependent variable (wave speed). The arrows in the figure show how Katie's hand traced out each column depicted by the dotted lines. Katie's suggestion evidenced her prior familiarity with 2-column tables as a mode for representing datasets since this experiment was the first for this unit. Addy's construction of a 2-column table in her notebook moments later suggested that Katie's suggestion made sense to her as a way of organizing their experimental data.

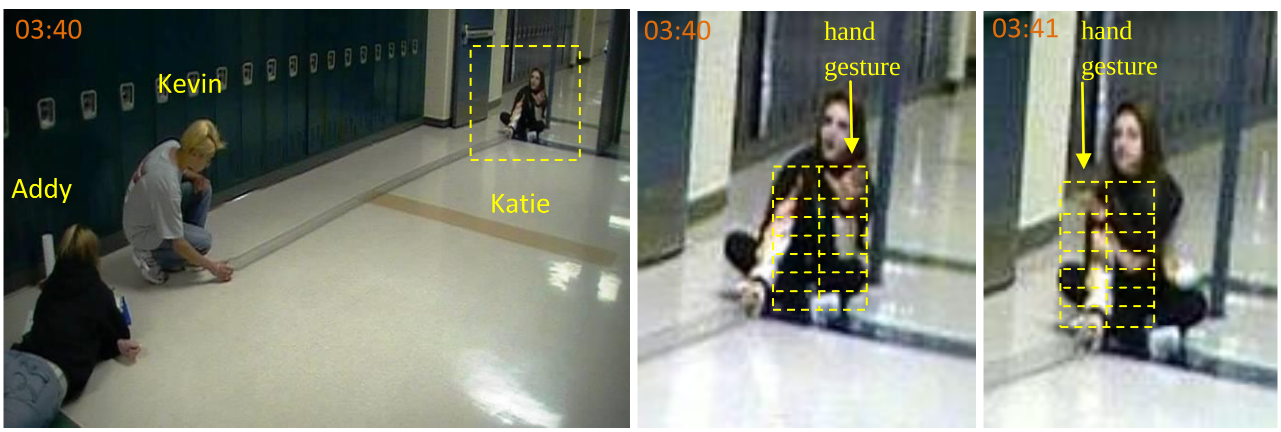


Figure 5.2.1. (Day 2, 03:40-1). Katie gestures to envisage a table. The dotted-line table in the middle (03:40) and right (03:41) photographs show the table Katie envisions.

In addition to organizing data sets, students used tables to interpret relationships in datasets. After the focal group finished collecting data, they immediately began to review their data table. They analyzed their data in light of the changes in height and speed, variables that they had measured and calculated (using measurements of time and distance) respectively. This process required students to first understand what the values in their table represented about the artifacts in the experimental setup, and then interpret how changes to the values of one quantity affected the other. The focal group's data table was structured in columns by the variables measured or calculated, namely height, time, speed, and distance (which the students also called "length" since the distance the wave traveled was the length of the slinky). In each column, the group had listed the values of individual trials (Fig. 5.2.2). As students recorded data in the table, they had the opportunity to consider each point as both an individual measurement derived from the experimental context, and as a constituent of a larger dataset.

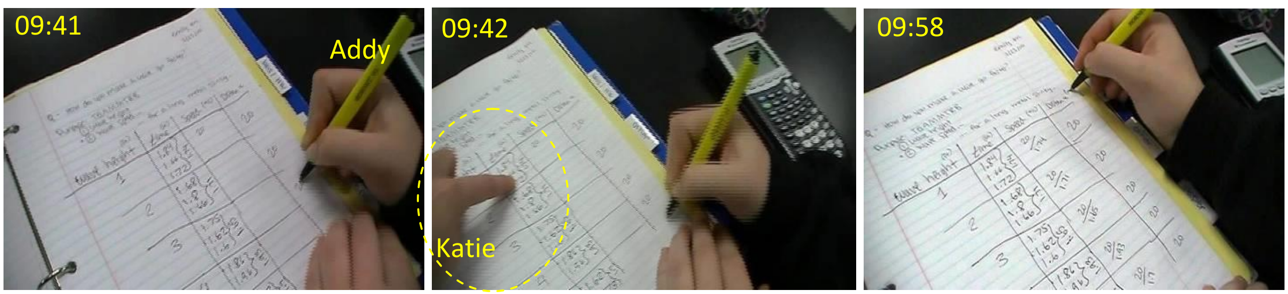


Figure 5.2.2. (Day 2, 09:41-58). The data table that the focal group constructs during the wave height vs. speed slinky experiment.

Engaging with tables encouraged students to consider the units of their measurements, which were determined by the devices and artifacts students used during an experiment. Students were compelled to consider the units of each quantity they measured or calculated as they labeled each column in their table. For example, in the slinky experiment, the groups measured the initial height they gave to a wave pulse in a slinky and the elapsed time for it to travel the slinky's length. Each of these measured values, and speed that was calculated using these values, became a column in their table shown in Figure 5.2.2. Their written labels included (“Wave Height (ft), [elapsed] time (s), speed (m/s), distance [or slinky length] (ft)) contained units in parentheses. The practice of labeling the table with the quantity and its units stemmed from students’ past experiences in my class, and reflected the grammar for constructing data tables. It also promoted students’ conceptual engagement with their data as students questioned if the data made sense or not, converted between related units (e.g., feet to meters), and identified patterns that strengthened the development of conceptual and empirical relationships.

The units were foregrounded by the labels students wrote in their tables. Labeling both values and units for each variable was part of the grammar for data tables, which enabled and promoted students’ consideration of units as they constructed tables. In the focal group’s table, Addy made a new column for the length of the slinky, which had a constant value of 20 [feet] (shown in Fig. 5.2.2, 09:41). As Katie suggested that Addy determine the speed values by dividing the distance column’s values by the time column’s values, Katie pointed to each of the columns (shown in Fig. 5.2.2, 09:42) manifesting her understanding of speed as a rate of distance traveled (i.e., the slinky’s distance [or length] shown in one of columns Addy had created) over the time that Addy had measured with the stopwatch. Katie was able to distinguish the height column from the length column in terms of which one should be used to calculate speed, even though they both represented a measure of distance in units of feet. In addition, as soon as Addy labeled the slinky distance column with feet as units, Katie suggested that instead of feet the units should be meters, as it was typically done during experiments prior to those in the waves unit since I had consistently required students to express all final numerical values in standard units (e.g., meters, seconds, etc.). Addy agreed and changed the “20” to “6.09 m” converting to meters using a conversion factor she already had committed to memory, and then wrote down the speed values that Kevin was calculating using his calculator distance values in meters.

The students primarily negotiated the meaning of data in relation to units via verbal exchanges with one another in the context of their data tables. However, these verbal exchanges also involved references to the artifacts used in their experiments. Figure 5.2.3 contains the multimodal transcript of the focal group's engagement with converting the wave height values from feet to meters. Similar to recognizing that the slinky's length values needed to be converted from feet to meters, Addy later recognized that the wave height measurements were also in feet and needed to be converted to meters. Agreeing with Addy, Kevin suggested that she *divide* the measurements in feet by 3.28 to convert them to meters, but changed to *multiply* when Addy repeated his suggestion to divide. Addy, though, challenged his change and referred back to the conversion of the slinky's length from feet to meters by *dividing* (Unit 5), which Kevin had then correctly suggested. Although Addy's utterance in Unit 7 appeared largely mathematical, she also seemed to be making sense of the correspondence of 20 feet with 6.09 meters in a spatial way since she knew how long the slinky appeared to be. Her spatial reasoning made sense to Kevin too, who realized his mistake and agreed with Addy. His utterance in Unit 12 was significant because instead of simply agreeing like he did in Units 8 and 10, he then reasoned mathematically about Addy's point demonstrating his engagement with her idea and his own understanding. Addy's spatial reasoning instead of using algebraic arguments that are more abstract and removed from the context show the role that the actual experimental setup had on students' construction of concepts. Her utterances and thinking were connected to her engagement with the slinky as an artifact.

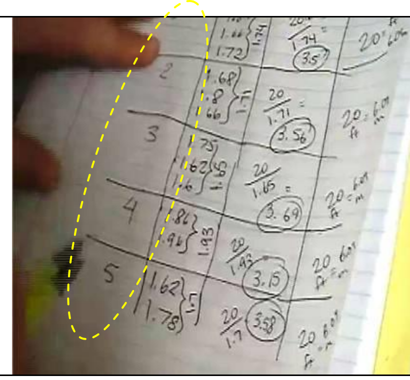
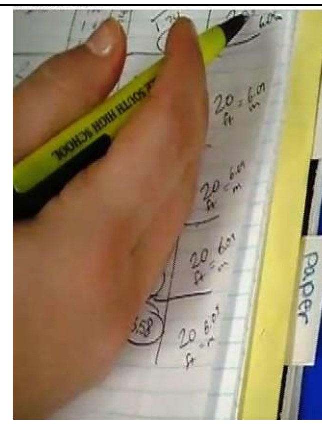
1	Addy	We have to convert these feet to meters, right? [*points to* wave height *column as she speaks, which is denoted by the dotted circle in the photo to the right*]	
2	Kevin	Yeah, so you have to divide them, no multiply by 3.28	
3	Addy	[*2 second pause*] Wait! You said divide?	
4	Kevin	No multiply.	
5	Addy	Well these I divided. [*points to the distance (slinky length) column seen in the photo to the right*]	
6	Kevin	Oh.	
7	Addy	20 feet divided by 3.28 is like 6.09 meters, that makes sense.	
8	Kevin	Oh okay.	
9	Addy	Doesn't it?	
10	Kevin	Right right okay	
11	Addy	So you do one foot divided by 3.28	
12	Kevin	Right 'cause a foot is smaller than a meter, I'm good.	

Figure 5.2.3. (Day 2, 11:00-11:28). Multimodal transcript of focal group's discussion around their data table during the first slinky experiment. Kevin and Addy are sitting down next to each other at a table while Katie is standing behind them videotaping. Addy is writing.

Graphing was another modality in which students engaged while exploring experimental datasets. Both modalities, graphs and tables, provided opportunities for students to make meaning of the relationship between two variables but in different ways. The curve in a graph depicted the relationship that could only be inferred from a data table.

Upon reviewing the data they had collected and organized into the table shown in Figure 5.2.4, the focal group identified a non-covariant relationship that they communicated in a free-hand graph. Every student in the focal group noticed at various points throughout the lesson that the stopwatch times, and therefore the speeds, did not really change as the wave height was varied. After examining their data table, the group concluded that the wave height had no effect on the wave speed based on the lack of change in the time, and therefore speed, values. Addy decided to sketch a free-hand graph in her notebook to express the relationship between height and speed as shown in Figure 5.2.5. I had not requested that students draw a graph in their notebooks; Addy chose to draw it on her own. She turned to the graphical modality to describe and talk about the relationship instead of the data table. She reduced all the data to a simple shape (a flat line) on a graph that highlighted the relationship of the values of the two variables. The shape of the graph was the relationship at which the group had arrived. Addy's understanding of how to sketch the shape of the free-hand graph's zero-slope best-fit line based upon the data table represented her understanding of the relationship between these two variables. Her shift from using a table to creating a line graph, not only communicated her conceptual understanding, but also strengthened it not only for her but for the other students too.

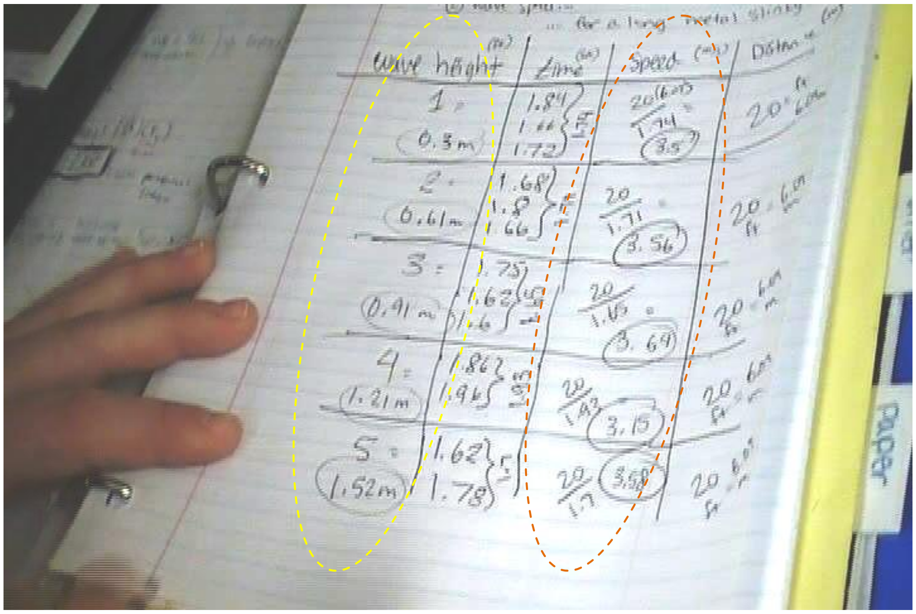


Figure 5.2.4. (Day 2, 12:00). Focal group's final version of their data table they used to infer an empirical relationship for the first slinky experiment. The wave height and speed columns are denoted by yellow and orange dotted circles respectively.

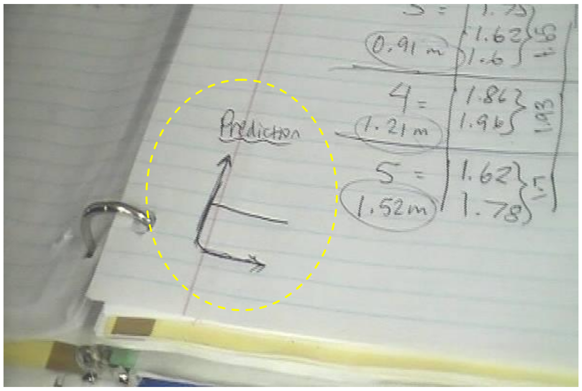


Figure 5.2.5. (Day 2, 12:26). Focal group's initial free-hand graph inferred from their data table for the first slinky experiment.

The transduction from the data table to the graphical modality forced Addy to describe the relationship in a new modality, whose grammar afforded modifications to her understanding of it. She was able to look beyond the small variations in the dataset due to random error, which were evident in the table, and sketch a straight and flat line that represented how the relationship should appear accounting for the presence of random error. Had she not made this modification during her shift from one modality to the other, the line she would have sketched would be crooked to include the small variations due to random error. By transducing to a line graph, she not only foregrounded the relationship through the shape of the line, but also backgrounded the quantitative aspects of the data, which were so prominent in the table. Since her free-hand graph lacked numbers on the axes, she lessened the significance of the individual values in exchange for calling attention to the significance of the relationship between the variables. In addition, Addy's decision to create a free-hand graph demonstrated the value she had assigned to graphing as a modality.

Although Addy was the one who drew the graph, the other group members supported her. Just before sketching the line graph, Addy verbally shared that she expected the graph's curve to be a "straight line," when Kevin interrupted her saying, "a horizontal line," and she quickly agreed with his more specific description. This indicated that Kevin and Addy shared a common understanding of the non-covariant relationship between wave height and wave speed within the graphical modality so that they could both shift from the two-column data table to a line graph. Although the axes in their free-hand graph were not labeled, it can be assumed that they knew speed was to be on the y-axis and height on the x-axis based on their discussion of the data prior to the sketch, how they later entered data into the computer in a similar way, and the eventual more detailed free-hand graph Katie produced on their team's whiteboard shown in Figure 5.2.6.

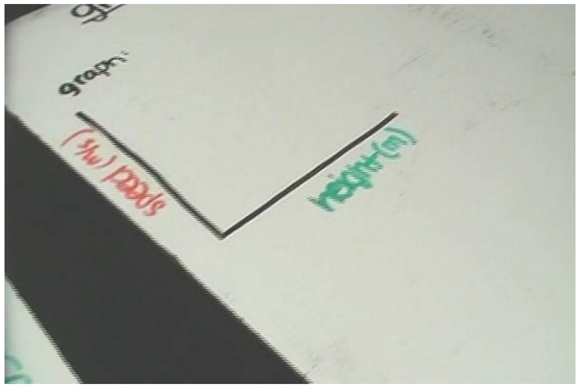


Figure 5.2.6. (Day 2, 12:59). Focal group's initial free-hand graph for the second slinky experiment.

The ways in which students used graphs (free-hand or computer-generated) to make meaning of relationships between sets of values was critical for understanding how students made sense of relationships between wave characteristics since each set of values mapped onto a wave characteristic. When students drew free-hand graphs, they had to choose in what way to sketch the graph based upon their conception for the grammar of that modality, and in particular, which features to include or exclude. Katie sketched the axes of free-hand graph onto the whiteboard before the group had entered their data into the graphing software. The features that Katie included in the free-hand graphs shown in Figures 5.2.5-6, and the graph corresponding to Unit 8 in Fig. 5.2.8, coupled with her group's verbal exchanges during its creation, reflected the group's conception of the grammar for free-hand graphs. This grammar corresponded to a hybridization of diagrammatical and graphical grammars since a free-hand graph was a diagram of a graph. There was an ongoing dialogic relationship between the diagrammatical and graphical grammars occurring within the construction of the grammar of free-hand graphs. The ways in which students created diagrams shaped the way in which they created free-hand graphs, and the ways in which students engaged with computer-generated graphs also shaped how they created free-hand graphs.

The computer-generated graph, though, which the focal group constructed after their free-hand graph, did not appear to match the relationship they inferred from the data table. The regression performed by the computer program displayed a slope of -0.08029, which represented a relationship close to zero, yet not exactly zero. Moreover, the axes of computer-generated graphs are automatically scaled to fit the datasets being plotted, but can be rescaled by the user. After the focal group entered their experimental data into the computer's graphing program, they obtained the computer-generated graph shown in Figure 5.2.7a. Katie instantly recognized that "you have to make this bigger 'cause the interval is too small," as she pointed to the y-axis on the screen. Katie was referring to the scale or range of the y-axis being too small, and therefore in need of expansion. As she spoke, Kevin increased the scale of the y-axis and as a result the graph appeared more like their hand-drawn graph (i.e., a flat line), as shown in Figure 5.2.7b. Katie then suggested they performed a linear regression, so Kevin chose a best-fit line to be included in the computer-generated graph (Fig. 5.2.7c). Their understanding of how this relationship should be represented within the graphical modality was evident by their recognition that in order to identify the trend line in the computer-generated graph in Figure 5.2.7a they had to expand the range of the y-axis, and that the trend line should be a straight line.

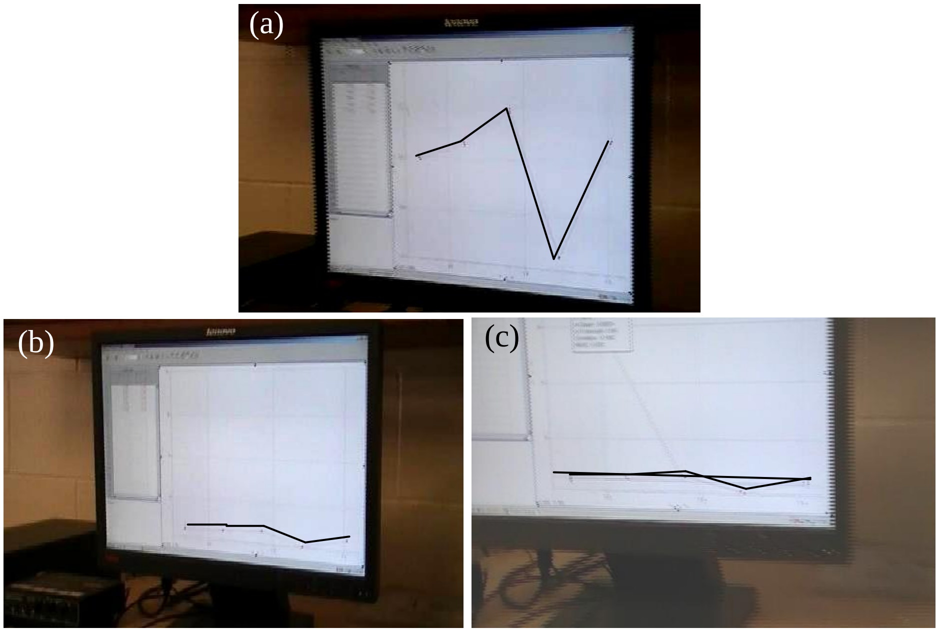
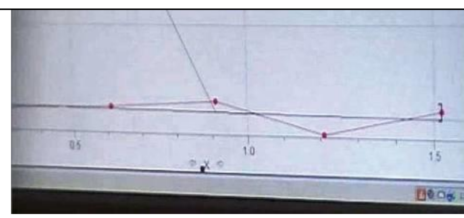
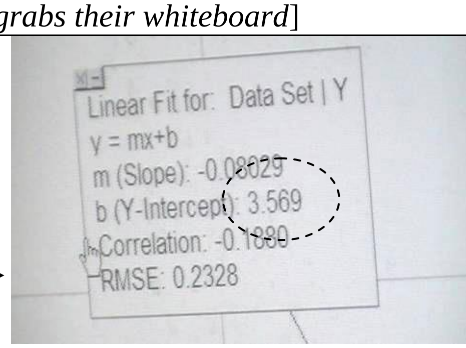


Figure 5.2.7. (a), (Day 2, 14:16). Initial computer-generated graph during first slinky experiment, before any student modification. (b), (14:18). Re-scaled computer-generated graph. (c), (14:23). Re-scaled computer-generated graph with a best-fit line.

Rescaling the axes helped provide the students visual agreement between the graphs they derived from the table and the computer-generated one. Based on the zero slope empirical relationship they derived from the table, the focal group was able to recognize that something was wrong with the initial appearance of the graph and choose to rescale it. By understanding the grammar of the graphical modality, the focal group was able to produce a computer-generated graph that was similar to the free-hand graph they had generated from inspecting their data table. However, although the two graphs were similar, they were not identical; the slope value generated from the computer's regression was not exactly zero like the slope of the free-hand diagram. The best-fit line already accounted for random error, but was limited by the number of data points used to derive the slope. If a larger number of data were collected and plotted, the slope value, currently at 0.08029), would have been much closer to zero.

At the start of the transcript in Figure 5.2.8, the students in the focal group had just finished all of their manipulations of the computer-generated graph, and were beginning to decide which particular information from that graph should be included in their free-hand graph. The free-hand graph was sketched on a whiteboard that would be publically displayed during the whole-class discussion later in the lesson. Units 1-3 show how they reaffirmed their consensus that the relationship should be represented by a flat line as it was initially inferred. Kevin was able to reason that the best-fit line's nonzero slope displayed in the computer graph was likely due to the slight differences in the speed values.

<table>
<tr><td colspan="4">[Kevin has the computer perform a linear regression in which a best-fit line and regression data appear]</td></tr>
<tr><td>1</td><td>Addy</td><td>So yeah like zero [referring to the slope] =There should be no slope=</td><td rowspan="3"></td></tr>
<tr><td>2</td><td>Katie</td><td>=alright the slope is basically= zero, yeah</td></tr>
<tr><td>3</td><td>Kevin</td><td>Well probably due to the y-values, since they're like slightly different the slope is a little off [from zero]</td></tr>
<tr><td colspan="4">[15 second break in discourse as the group grabs their whiteboard]</td></tr>
<tr><td>4</td><td>Katie:</td><td>What's the speed, which would be the y-axis value?</td><td rowspan="3"></td></tr>
<tr><td>5</td><td>Kevin:</td><td>Oh, the average speed? Is uh [pause] what's the y-intercept value? 3.5 [pause] 7 [Kevin reads this value off the computer's regression]</td></tr>
<tr><td>6</td><td>Addy:</td><td>3.57 (says in agreement)</td></tr>
<tr><td>7</td><td>Kevin:</td><td>Meters per second</td><td></td></tr>
</table>

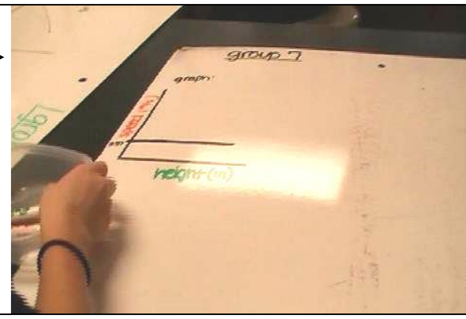
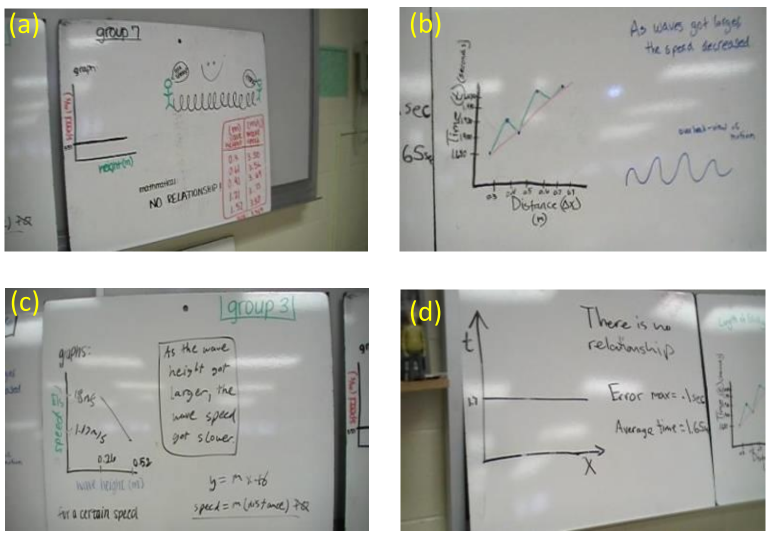
8	[*There is a break in the discourse as Katie finishes the graphical sketch on the team's whiteboard*].	

Figure 5.2.8. (Day 2, 14:43-14:58). Multimodal transcript of the focal group interpreting the computer-generated graph of their data from the first slinky experiment.

As the focal group transduced from their computer-generated graph to a free-hand graph, they were forced to appreciate the relationship in an approximate matter, which helped them realize that it was close to zero which they had already inferred from their data table. The focal group's free-hand graph that they constructed on their whiteboard only included pertinent information, such as the shape of the best-fit line and particular numerical values derived from the computer-generated graph and regression. Katie asked her team to obtain a speed value from the computer-generated graph (Unit 4) so she could label the y-intercept on the free-hand graph. Kevin's response in Unit 5 was only partially correct. He acknowledged that there was only one speed value, and that it should be an average of all of the speed values; however, he then incorrectly identified the y-intercept from the regression as the average speed. Although, Kevin made the mistake of treating the y-intercept as the average speed (y-value), these values would have been equivalent if the slope of the computer's best-fit line were actually zero. By the end of the transcript, the group determined the speed to be 3.57 m/s, which was the y-intercept obtained from the regression. The mean of all of their reported speed values would have been 3.49 m/s. These two values are close, but are obtained in significantly different ways. Thus, the students were not analyzing their data correctly, despite Kevin saying “average speed” in Unit 5. This did not impact the relationship they were exploring, but it did reveal a potential analytical setback and limitation to the use of the graphical modality that went unnoticed by both the students and myself at the time.

There were seven groups in the class and each group independently conducted the same experiment. After all of the groups finished and prepared a whiteboard summarizing their experimental results, we had a whole-class discussion of these whiteboards. As I noted in Section 4.2, I selected four of the seven whiteboards to publically display based on the diversity of the groups’ interpretations and findings (Figures 4.2.2a-d inserted below for the reader’s convenience). I displayed two correct interpretations and two different incorrect interpretations side-by-side so we could engage in a whole-class discussion about them. The whiteboard in Figure 4.2.2a was made by the focal group, and correctly concluded that there was no relationship (or zero-slope relationship) between wave height and wave speed. The group’s whiteboard in Figure 4.2.2d also presented a correct conclusion, but referred to the relationship between wave height and propagational time instead of wave speed, albeit time was indicative of speed, as time of propagation is inversely related to wave speed.

It was evident that the students whose free-hand graphs are shown in Figures 4.2.2b, c did not manipulate or rescale the y-axis of the computer-generated graph to a larger scale during their analysis, as the focal group had done. The default small range visually exaggerated the range and the best-fit line’s steepness. Since the y-axis was scaled so closely, a slight positive or negative slope appeared much steeper than if a larger scale were used instead. This must have led them to not recognizing the value of the slope as being approximately zero. As a result, the group’s free-hand graph seen in Figure 4.2.2b had a positive slope, and the group’s free-hand graph in Figure 4.2.2c had a negative slope. In both cases, the limited ease with the graphical grammar regarding the need to rescale the computer-generated graph's axes in order to consider the value of regression slope was responsible for failing to derive the correct relationship.



Reproduction of Figure 4.2.2. (end of Day 2). Student-groups' whiteboards of wave speed vs. height slinky experiment. (a) is the focal group's board.

In contrast, both groups that correctly identified a non-covariant relationship (Figures 4.2.2a, d) inferred a relationship in light of the random error in their measurements. All of my students had encountered and analyzed random error in experiments leading up to this unit during which I had encouraged them to calculate a value for error using the difference between the highest and lowest values within a repeated trials dataset. They could then compare this difference to the difference between two values of the dependent variable for different values of the independent variable to determine if the latter did not exceed the former and, thus, might be attributed to random error. If the team recognized a non-covariant relationship at this point in their analysis, they were not required to produce a computer-generated graph, and could instead proceed directly to transducing a free-hand graph, as the focal group did with their free-hand graph in Fig. 5.2.5. Despite the focal group's confidence in the empirical relationship they derived from their table, they produced a computer-generated graph and considered the empirical relationship from it in light of the one they had inferred from the table. It was not known to what extent the group, whose board is shown in Figure 4.2.2d and similarly to the focal group inferred a non-covariant relationship, engaged with their data, or whether they had created a computer-generated graph or not. However, they listed a value for error and derived a non-covariant relationship shown in their free-hand graph. The value for error listed on their board suggested that they engaged with their data table enough to calculate a value for error, and at some point during the experiment, they were able to infer the non-covariant relationship which they graphically displayed on their whiteboard.

Following the experiment (Day 3), I facilitated a whole-class discussion about the experiment, and in particular, I focused on analytical considerations regarding the data in represented various modalities, to model and foreground the grammar of tables and graphs. This discussion included interpretation of tables that contained repeated trials for multiple values of the independent variable, and construction and analysis of computer-generated and free-hand graphs. I summarized the correct findings for their previous experiment (that there was a non-covariant relationship between a wave's amplitude and its speed), as I modeled appropriate data interpretation and analysis to guide students through the process of deriving an empirical relationship between wave height and speed using tables and graphs. At first, I presented them with a table of sample repeated trials data, shown in Figure 5.2.9. These data were values I created that were similar to data students measured during their experiments on the previous day. I provided this table to facilitate our class discussion on how to interpret and analyze random error in datasets. As previously mentioned, I had consistently encouraged students to consider the extent to which error might affect their measurements by conducting multiple identical trials, or *repeated trials*. Using these data, they could estimate a value for error as the difference between the highest and lowest values in the repeated trials dataset. In the sample data seen in Figure 5.2.9, the same height (0.3 meters) resulted in a variety of propagational times with the highest (2.02 sec) and lowest (1.72 sec) being approximately 0.3 sec apart. The same method was used for determining error (0.4 m/s) in the corresponding speed values that I calculated with these times.

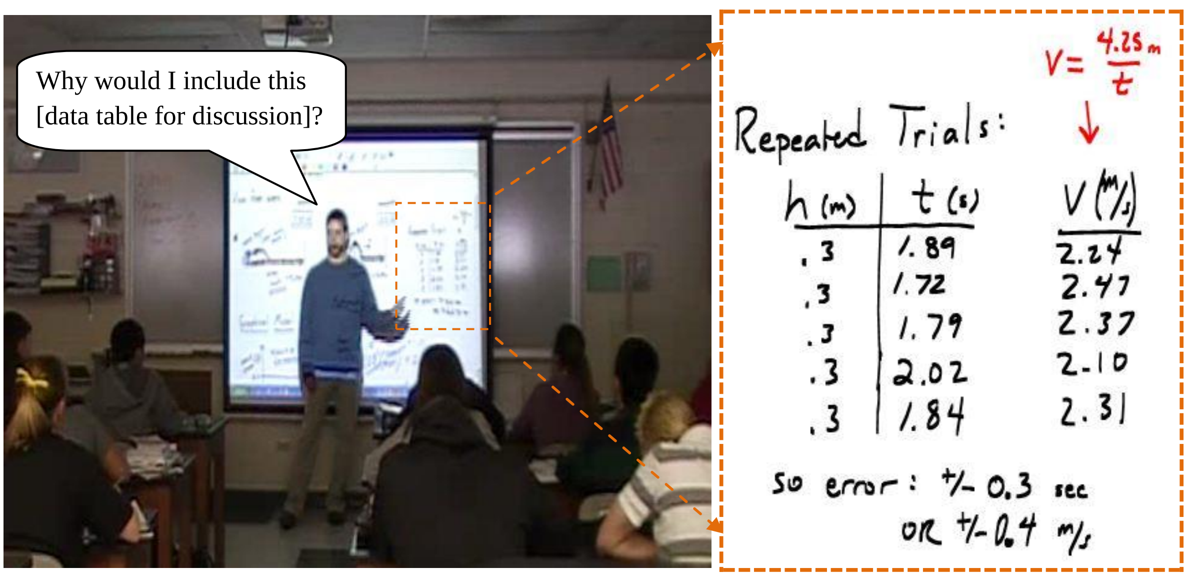


Figure 5.2.9. (Day 3, 5:40). My table of sample repeated trials during a post-experiment lecture.

Determining a value for error offered students a mathematically simple way to quantitatively assess a value for error, which they could apply to their analysis of the relationship by comparing this error to the difference in the highest and lowest values of the dependent variable dataset. A difference within the error would indicate a non-covariant relationship, which students could then transduce to a free-hand graph with zero slope. Significantly larger differences in the dependent variable than the error would suggest a covariant relationship that could be further explicated by generating a graph using the computer program, and then transducing it to a corresponding free-hand graph.

The purpose of our whole-class discussion of the repeated trials table was to consider random error in measurement and calculate a value for error. The discourse appearing in Figure 5.2.10 occurred at the beginning of our class discussion about the repeated trials data. Brian's contribution in Unit 6 showed confusion about how to interpret the sample repeated-trials dataset, in which all dependent variable values for the *same* independent variable value should be the same but which varied slightly due to random error. Brian apparently confused this repeated-trials dataset with the complete dataset, in which various values of wave height (independent variable) and wave speed (dependent variable) were shown, and which we had discussed in the previous day following the experiment.

Graphs are an appropriate modality to foreground the relationship between different values of independent and dependent variables, which in this experiment was a non-covariant one represented by a straight horizontal line. However, graphs are not a useful modality for representing repeated trials data since there was no underlying relationship. In the past, data tables often afforded transduction with the graphical modality, which was a cultural practice in which my students were immersed throughout the school year. Brian did not realize the difference between the repeated-trials dataset and the dataset that contains different values of independent and dependent variables and this might have led him to an inappropriate transduction to the graphical modality using the repeated trials data.

1	Teacher	Why would I include this [data table in my results]?
2	Raymond	All of the height values are the same and then we can clearly see that all of the time values are different.
3	Teacher	Okay so why did I show this? So what?
4	Raymond	There's error.
5	Teacher	There's error, good! Can anyone else pull anything out of this?
6	Brian	The values are really close together so like if it was plotted on a graph then it would be like a straight line, with like no slope
7	Teacher	Well if these were plotted on a graph, they have the same height value
8	Brian	Oh yeah, whoops
9	Teacher	So that's one thing that's confusing, this isn't showing me the data that I [should] graph

Figure 5.2.10. (Day 3, 6:10-7:00). Transcript during a whole-class discussion where students offered their interpretations of a repeated-trials data table.

Brian's confusion might have also been fueled by his prior engagement with the non-covariant graph during the previous day's whole-class discussion over the experimental results, coupled with the fact that the general topic of this discussion was the previous day's experiment. Brian and the other students had just discussed the zero-slope graph during the previous day's experiment. As a result, this might have encouraged his transduction to the graphical modality as well as suggested that the graph have a zero-slope best-fit line.

Students' understanding of the relationship between the slinky's wave height and its speed was predicated on their understanding of how to infer such a relationship from the data in both tabular and graphical modes. I modeled how students were to graphically understand the relationship using free-hand graphs during a lecture following the experiment (Day 3), so that they might utilize my techniques in other experiments they would conduct during the following day (Day 4). I drew a canonical free-hand graph seen in Figure 5.2.11a to represent the data derived from the previous day's experiment, which my students and I had already discussed during the previous day's discussion.

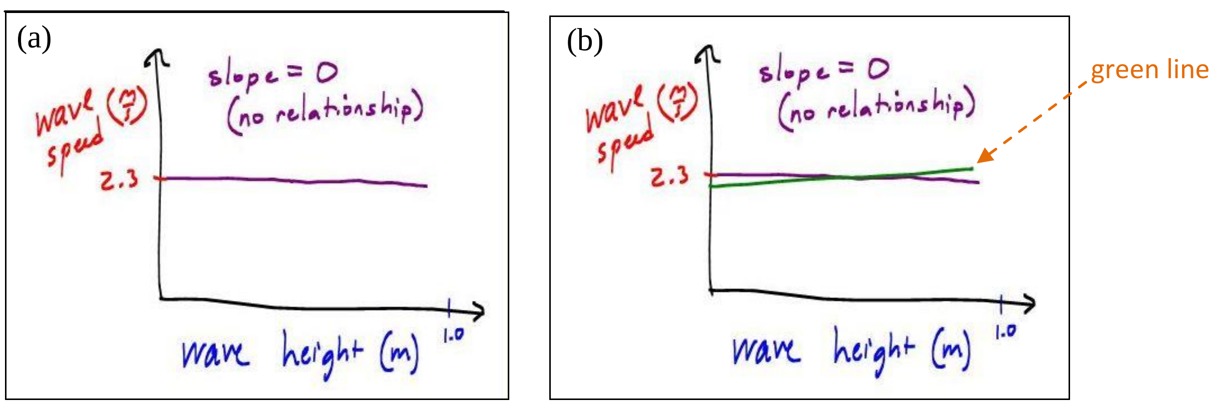


Figure 5.2.11. (a), (Day 3, 11:15) Teacher-drawn free-hand graph depicting a non-covariant relationship. (b), (11:30) Teacher-drawn free-hand graph depicting a non-covariant relationship that also includes the computer-generated graph's best-fit line (green line).

When sketching my free-hand graph, I made decisions about which graphical features to include, or not, in the same way that my students made decisions for their graphs they had sketched on their whiteboards on the previous day. The graphical features I intended to model for them, and had consistently encouraged my students to include in their free-hand graphs throughout the year are listed in Figure 5.2.12, and capture the grammar of free-hand graphs.

- Labeled axes (with type of quantity and units)
- Maximum values for each axis to display scale
- Best-fit line or curve ONLY
    - Do not include points nor "connect-the-dot" lines

Figure 5.2.12. The pertinent features of free-hand graphs.

The best-fit line or curve in any graph is especially important, as it represents the relationship among the data. A slight positive or negative slope was typical for computer-generated best-fit lines of non-covariant datasets with a limited number of data points, which was exemplified by the slight positive and negative slopes of the students' free-hand graphs shown in Figures 4.2.2b and 4.2.2c, respectively. The students' computer-generated graphs from the previous day's experiment often resulted in empirical relationships having nonzero values for slope. Since my instructional goal was for students to construct the canonical understanding that wave height and wave speed have a zero-slope relationship, I had to help them understand how to infer non-covariant relationships using computer-generated graphs. To achieve this, during the follow-up lecture, I drew an additional trendline (a green line) onto my free-hand graph to represent what a computer's best-fit line might look like. As seen in Figure 5.2.11b, this green best-fit line had a slight positive slope.

While explaining my free-hand graph, I used the width of my hand from my thumb on the bottom to my pinky finger on the top as a gesture to represent the existing random error as an interval or amount of change in the y-axis (Fig. 5.2.13). This gesture aimed at helping students to link random error to the graphical modality an interval quantity on the y-axis. Moreover, I wanted students to recognize that the computer-generated best-fit line (green line) did not contain values outside of the interval representing the amount of error in the dependent variable (y-axis) as seen in Figure 5.2.13. Although my free-hand graph was not a scaled graph, and thus my hand was not being used in conjunction with our actual value for error, my hand symbolized that the error was larger than the variation in the entire dataset being graphed, and publically transduced the concept of error to a free-hand graph. I then reminded students that they could bypass creating a computer-generated graph if they recognized the relationship had a zero slope during their analysis of the tables.

Following the lecture, students conducted two more experiments (Day 3) again using the slinkies: wave speed versus period (related to frequency), and wave speed versus slinky-length. Unbeknownst to the students prior to the experiment, there was a non-covariant relationship between a wave's speed and its period (and frequency) that students were to derive from their data. The experiments offered students an opportunity to engage with tables and graphs in light of the various ways we had shared and discussed during the previous slinky experiment.

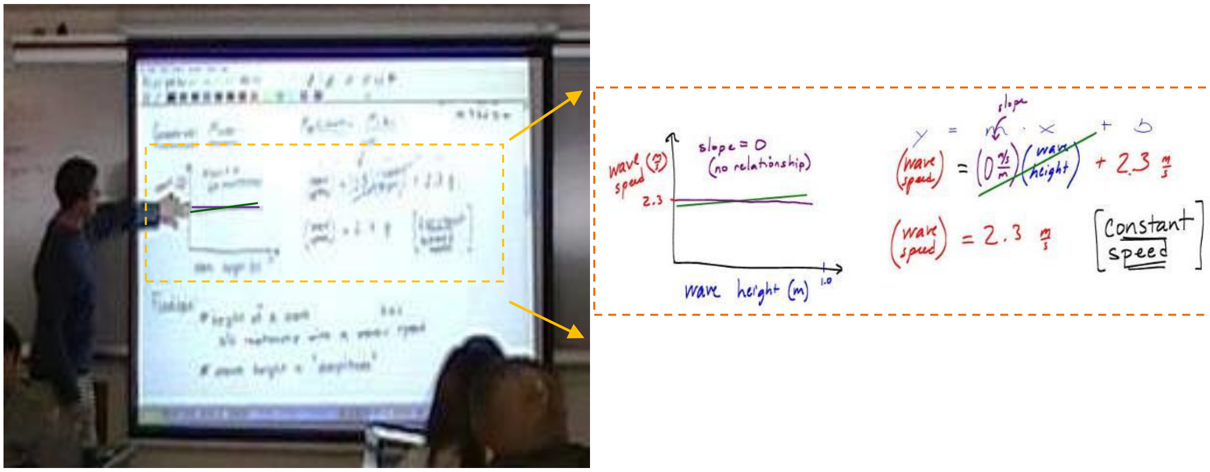
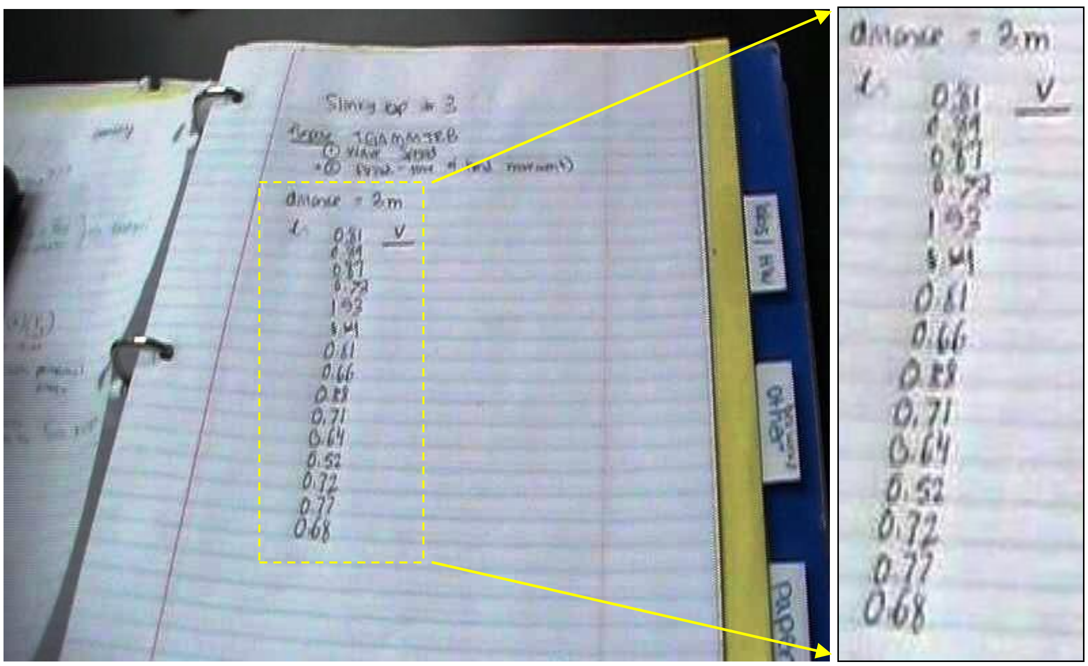


Figure 5.2.13. (Day 3, 12:03). The width of my hand from my thumb on the bottom to my pinky finger on the top represented the interval or amount of change in the y-axis that could be attributed to random error.

The focal group was assigned the speed vs. period experiment in which they again used a stopwatch to measure the time each wave took to travel the fixed slinky length in order to later calculate the wave's speed, and a motion sensor facing the student's hand to measure the period as the wave was created (i.e., the time for the hand to move back and forth as it created a wave in the slinky). The focal group conducted 15 trials and recorded all of the stopwatch values into a table in their notebook seen in Figure 5.2.14. The listed times were all stopwatch times for the wave to travel the 3-meter fixed length of the slinky. The period values captured using the motion sensor were not listed in the notebook, but were stored on the students' computer for them to individually match with the stopwatch times (e.g., propagational values) later during their analysis of the data. After the data collection, the focal group students realized that the process of matching the propagational values with the period values derived from the motion sensor's graph on the computer would be too tedious, and instead decided to only use the first three and the last three trials during their analysis during the next lesson.



distance = 3m

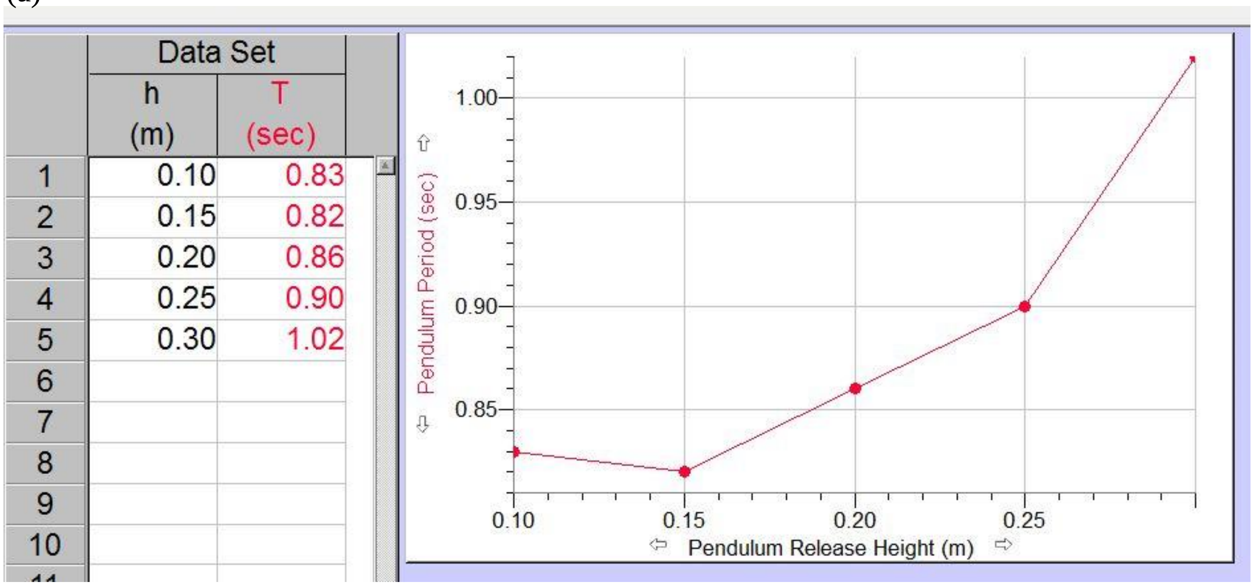
t:	v
0.81	
0.89	
0.89	
0.73	
1.53	
0.61	
0.81	
0.66	
0.88	
0.71	
0.64	
0.52	
0.72	
0.77	
0.68	

Figure 5.2.14. (Day 3, 46:17). The focal group's table of propagational time values from the second slinky experiment (period vs. wave speed). The table is typed to the right for increased readability.

The next day (Day 4), before beginning their analysis of the data they collected during the previous lesson, the students worked independently on a brief quiz. The quiz aimed at promoting appropriate transduction of data in a table to a free-hand graph taking under consideration random error. Students were provided with sample data from an unrelated and hypothetical experiment

(Fig. 5.2.15a, b). I projected the sample dataset table and its corresponding computer-generated graph shown in Figure 5.2.15a. The students had never conducted this particular experiment–a pendulum experiment to determine the relationship between a pendulum's release height and its period, so they were unaware of the underlying relationship. The handout portion of the quiz (Fig. 5.2.15b) provided each student with a description of the experiment, a table of repeated trials from one of the height values (0.2 m), and two sample interpretations from which students were to select one and then explain their choice. Students had to determine whether the relationship between the two variables was a quadratic relationship represented by the apparent parabola on the computer program's graph, or a non-covariant relationship that only appeared to curve on the graph due to random error in each data point and a lack of a large number of data points.

(a)



(b)

Bell Work: (2/25/10) **Name:**

Students conducted a pendulum experiment to graphically represent the relationship between a pendulum's period and its release height. Sample data from this experiment is projected on the screen.

During this experiment, repeated trials were done for each data point. One of those data point's repeated trials are shown in the tableto the right:

height	period
0.2	0.98
0.2	0.81
0.2	0.75
0.2	0.90

How would you explain the trend in this data? Meaning, is the shape of the graph an actual trend in the data, or could the false trend be created by random error in the measured values? Describe your interpretation of the relationship (or lack thereof) between these two variables, and explain your reasoning for how you'd make sense of the shape of the graph projected on the screen for this experiment.

Figure 5.2.15. (Day 4). (a), Sample dataset and graph projected in front of the class during a brief quiz. (b), Handout of the brief quiz students worked independently.

After students finished the quiz, I asked for volunteers to share their choice and reasoning. Three students responded verbally explaining their reasoning, and immediately the first student, Zeke, began referencing the repeated trials data table (Fig. 5.2.15b) projected on the screen in front of the class by pointing with a laser pointer. His response is shown in the transcript in Fig. 5.2.16.

<table>
<tr><td>1</td><td>Zeke</td><td>Uh the difference between the highest one which is .98 and uh .75 is .23 which is the error because you'd expect that to be the same, um so you get that just to find the average, and then uh you go back uh</td><td rowspan="2"><table><tr><th>height</th><th>period</th></tr><tr><td>0.2</td><td>0.98</td></tr><tr><td>0.2</td><td>0.81</td></tr><tr><td>0.2</td><td>0.75</td></tr><tr><td>0.2</td><td>0.90</td></tr></table>[from Fig. 5.2.15b]</td></tr>
<tr><td>2</td><td></td><td>[3 second pause as I switch from projecting the handout (Fig. 5.2.15b) to projecting the graph (Fig. 5.2.15a)]</td></tr>
<tr><td>3</td><td>Zeke</td><td>um, you find the difference between the highest which is 1.02 and 0.82, the difference is .2, so since the amount of error is basically the same, then you can tell that uh it should be no trend.</td><td><table><tr><th></th><th colspan="2">Data Set</th></tr><tr><th></th><th>h
(m)</th><th>T
(sec)</th></tr><tr><td>1</td><td>0.10</td><td>0.83</td></tr><tr><td>2</td><td>0.15</td><td>0.82</td></tr><tr><td>3</td><td>0.20</td><td>0.86</td></tr><tr><td>4</td><td>0.25</td><td>0.90</td></tr><tr><td>5</td><td>0.30</td><td>1.02</td></tr></table>[from Fig. 5.2.15a]</td></tr>
</table>

Figure 5.2.16. (Day 4, 3:29-4:18). Transcript of Zeke's interpretation of the random error in the data provided during the brief quiz.

Zeke's utterances demonstrated his understanding of determining relationships in datasets through his engagement with, and transduction between, modalities, and more specifically between numerical lists or tables and graphs. This was also the same method of analysis I had suggested during my lecture on Day 2 in the context of the wave speed versus wave height experiment. At the end of Unit 1, Zeke said "and then uh you go back," at which point I switched from projecting the repeated trials data (Fig. 5.2.15b) to the graphing software screen (Fig. 5.2.15a). Zeke's utterance in Unit 1 represented his understanding of how to calculate a value for error, which led to his conclusion in Unit 3 that there would "be no trend" (i.e., a non-covariant relationship). He first considered the highest and lowest values in the repeated trials to determine a value for the random error, and then applied that value for error to the dependent variable dataset that was both listed in a table and plotted in the computer-generated graph. He examined if the change in the dependent variable was significantly larger than the value for error he had just determined. Since the highest and lowest period values did not vary by any amount larger than the period values measured for the repeated trials, Zeke concluded that there was no [covariant] relationship between the pendulum's release height and the pendulum's period.

After Zeke's response, Dustin then offered his interpretation, which is shown in the transcript in Figure 5.2.17. Dustin essentially presented again Zeke's response, but in his own way. Aside from assigning value to Zeke's response by publically agreeing with him, Dustin added his interpretation of the data that he referred to as not "scientific." He considered the changes within the entire dataset and noticed from what he perceived as a common sense point of view, that if the values were within 0.15 of each other, then they were not changing by very much. It was unclear how exactly Dustin derived the 0.15 value, and to what exactly the 0.15 was referring. In the plotted dataset, the lowest stopwatch time corresponded to a height of 0.15 meters, and the largest time to height a 0.30 meters. The difference in these values was 0.15 meters, and could be the difference to which Dustin was referring. This was how Addy interpreted his comment, which she would later refer to in Unit 3 of the transcript shown in Figure 5.2.18. Dustin was considering how the two variables change in relation to each other. Dustin felt that an increase of only 0.15 meters of height was too small of an interval and that the change in the stopwatch times that occurred over it lacked a coherent pattern to which he referred to as "butchered." Although other students, such as Brian, were using the ideas we had discussed in class, Dustin offered a new idea, namely that there was no trend in the data because the range was too small. However, he expressed doubt about his interpretation by prefacing it as an idea that "isn't scientific."

1	Dustin	I did exactly what Zeke did and I agree with him because I'm pretty sure that's how you find error, how Zeke did, and yeah how he took biggest and the smallest and subtracted 'em and it was uh 0.23, and then can you go back? [*he is requesting that I switch from projecting the handout (Fig. 5.2.15b) to projecting the graph (Fig. 5.2.15a) as I did for Zeke moments earlier*]	height | period 0.2 | 0.98 0.2 | 0.81 0.2 | 0.75 0.2 | 0.90 [*from Fig. 5.2.15b*]
2	Dustin	And also if you look, and this isn't scientific, but if you look at the uh numbers it's just like .15 off, and to have a trend that like that's like that butchered in that little amount, I don't know it just kinda seems like error	Data Set h (m) | T (sec) 1 | 0.10 | 0.83 2 | 0.15 | 0.82 3 | 0.20 | 0.86 4 | 0.25 | 0.90 5 | 0.30 | 1.02 [*from Fig. 5.2.15a*]

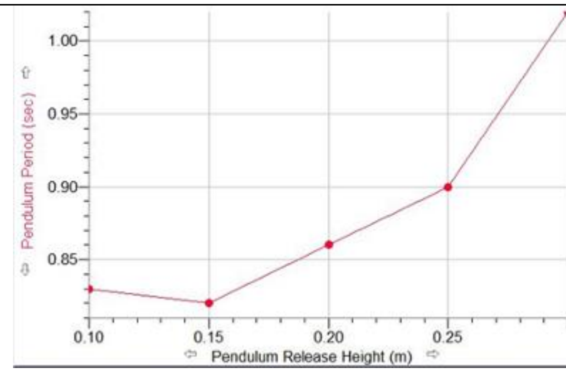
Figure 5.2.17. (Day 4, 6:02-6:43). Transcript of Dustin's interpretation of random error in the data provided during the brief quiz.

A key element within both Zeke and Dustin's responses was their choice to only analyze the data tables, instead of the graph, and in particular to not allow the curving shape of the graph to mislead their development of the relationship between the two variables. They engaged with the two different tables of values presented in a particular order: the repeated trials table was used first to assess a value for error, and then that error value was applied to the table of the complete dataset of the independent and dependent variables. This was critical to students' construction of relationships from experimental data. This process involves much more than assessing variations within a dataset presented in a table. Students must be able to distinguish repeated trials data from complete datasets, and engage with each appropriately. As previously seen in Brian's contribution in Unit 6 of Fig. 5.2.10, he confused the repeated trials dataset with the complete dataset, and inappropriately shifted from the repeated trials data table to a graphical modality, suggesting that the plotted best-fit line would be "a straight line, with like no slope." As compared to Zeke and Dustin's contributions shown in the transcripts in Figures 5.2.16 and 5.2.17, Zeke, Dustin, and Brian all recognized that the data were too close together, but Zeke and Dustin were able to correctly identify and differentiate between the repeated trials data table and the data table of the complete dataset of the independent and dependent variables that was plotted. Zeke and Dustin recognized that the shape of the computer's graph was misleading due to the small range exaggerating the curve. Their ability to choose modalities that they considered most appropriate, disregard modes completely or critically consider features of a particular mode, and transduce between modes indicated and shaped student learning and my class's shared understandings regarding how to derive empirical relationships.

When identifying non-covariant relationships, the benefit of student engagement with data represented in tables might lie in a table's prominence of individual *values* as opposed to a graph's prominence of a collective set of values represented by a curve's *shape*. By looking at the individual values, my students and I could easily estimate random error by identifying the high and low numbers of the dependent variable for the same value of the independent variable and subtracting them to obtain a measure of error.

In contrast to tables, graphs foreground the relationship in a dataset; that is, in graphs, it is not the individual values that are pronounced as it is the case in tables, but it is the shape of the line or relationship described by the set that is most prominent. Since I noticed that some of my students turned to tables as a modality to help them interpret error and especially to differentiate between non-covariant and covariant relationships, I asked my whole class which modality they considered it was better to use in order to analyze error and identify "false" trends (i.e., empirical covariant trends for non-covariant relationships). I created spaces to invite the students to overcome the challenges presented by the technology and auto-scaled graphs in particular. The students may not be able to fully control the format or appearance of data in the technological outlet initially provided. However, they can and should learn to correctly interpret the data and modify the data appearance in light of their understanding. Without understanding the underlying grammar of the modality afforded by the technology in a particular lesson, the students may be misled by the appearance, making this concept critical to students' successful engagement with data. Students' responses to the question I posed to the class are shown in the transcript in Figure 5.2.18.

In Unit 1, Addy used the laser pointer to point out the graph's shape as a prominent feature that might be misleading. A critical aspect of her thinking was her explanation of how the graph could be manipulated to show a different shape by increasing the scale of the y-axis, which would allow the curve to appear flat. Her idea can be linked back to her groups' actions and interpretations during the first slinky experiments in which she and her group successfully inferred using the table that the relationship was a non-covariant one, and then matched it to the computer-generated graph's shape by rescaling the graph. Their ability to interpret the measurements in the table and their understanding of the graphical grammar afforded them to rescale the computer-generated graph, and not to be misled by the appearance of the computer-generated graph's shape.

1	Addy:	I just think for me, I would say that the table is easier, like graphs can be interpreted all different ways, like because of this [*uses a laser pointer to trace along the graph's curve*] it looks like there is a trend where there is really not or at least I don't think there is, so like for me a data table is easier, um unless you like make this [graph's scale] like bigger	 (*from Fig. 5.2.15a*)
2	Teacher:	What do you mean make it bigger?	
3	Addy:	Like make it, like what Dustin said, this is only like, from the lowest to the highest, like .15	
4	Teacher:	Okay, like what do you want me to do here? [*I am in control of the computer and am asking her to tell me how I can manipulate the graph*]	

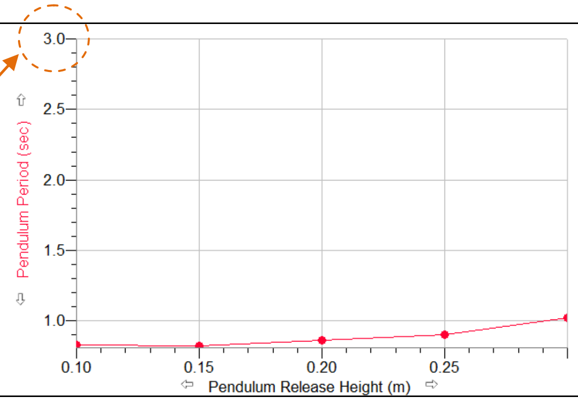
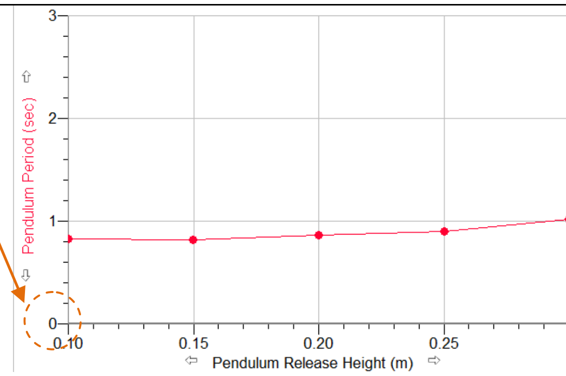
5	Addy:	Like, I think make the top point bigger, to like 3 [*I reset the maximum y-axis scale from 1.00 to 3.0*]	
6	Teacher:	No we can make anything look like a flat line ya know just by rescaling so we have to be careful, right?	
7	Zeke:	Wait, can we just make the bottom one go to zero?	
8	Teacher:	Yeah, I think that's reasonable to do to let the bottom to zero in a lot of cases [*I reset the minimum y-axis scale from 0.80 to 0*] 'cause I think you guys are saying, correct me if I'm wrong, Graphical Analysis is going to go right to a really small scale like it's gonna autoscale it right in zoomed in on it, so we may want to zoom out a little bit just to put it in perspective. Yes, Dustin? [*calls on Dustin*]	
9	Dustin	Yeah uh, I think the table's better, like I did that first, and then also if you look at this axis [y-axis], the numbers are too close together [*refers to scale of the original graph's y-axis*]	

Figure 5.2.18. (Day 4, 8:16-10:28). Transcript of students' comments on the use of tables versus graphs to interpret error.

In Unit 5, I publically rescaled the graph projected in front of the class just as Addy suggested, and cautioned the class about rescaling since the process could make almost any curve appear flat–even for covariant relationships. If students rescale without interpreting their data and its error beforehand, rescaling might lead to identifying a non-covariant trend where there is really a covariant one. Given this limitation, I had discussed with my students the idea of rescaling at various points throughout the year leading up to this unit encouraging them to consider expectations that they first inferred from their data tables We had also discussed that when the y-axis range was really small, rescaling could be done by increasing the maximum or resetting the minimum to zero. For this reason, when Zeke, in Unit 7, suggested that we could reset the minimum to zero instead of the maximum to a higher value, I agreed with him and demonstrated this to the class.

Continuing the focus on the students' experimental data (i.e., wave speed vs. period, or wave speed vs. slinky length), I assigned each group to answer three questions listed in Figure 5.2.19a. The focal group's final answers are shown in Figure 5.2.19b. The focal group students answered the questions quickly and with little debate, and determined that there was no relationship between their variables. Addy offered her reasoning to justify their conclusion saying "no relationship because on Tuesday, [Day 2, during the first experiment–wave speed vs. wave height] we actually did that, like we thought about experimenting if it was like to move it [the hand holding the slinky] faster, which is exactly what we're doing here." Going along with Addy's idea, Kevin then added, "yeah, so it's a flat line."

After completing the three questions, each group prepared a whiteboard displaying their experimental results that they would share with the rest of the class during another whole-class discussion. The focal group's negotiation of how to draw the free-hand graph is listed in the transcript in Figure 5.2.20. In Unit 1, Katie sought help from her group to decide which quantity should be plotted on which axis. She said, “y depends on x,” but then transitioned to thinking about which quantity they had chosen the values for. In Units 1 and 3, Katie and Addy indicated a shared understanding and familiarity with the word “choose,” which was commonly used by the students and me throughout the year to determine which quantity was the independent variable and should be plotted on the x-axis. Addy and Katie’s interaction, coupled with their previous experiences prior to this unit, shows that their collective understanding of the independent variable as the values selected by the experimenter and plotted on the x-axis was part of their group’s graphical grammar. This grammatical element of graphs was followed not only by the students in the focal group, but also by the rest of the class who constructed graphs in this way as evidenced by the agreement between which quantities were plotted on the x- and y-axes of the free-hand graphs on various groups’ whiteboards (see Fig. 4.2.2, 4.2.6, & 4.2.7). This suggested that plotting on the x-axis the quantity whose values were chosen by the experimenter was a shared cultural practice in my class, and an element of the collective graphical grammar for the majority of my students.

(a) (b)

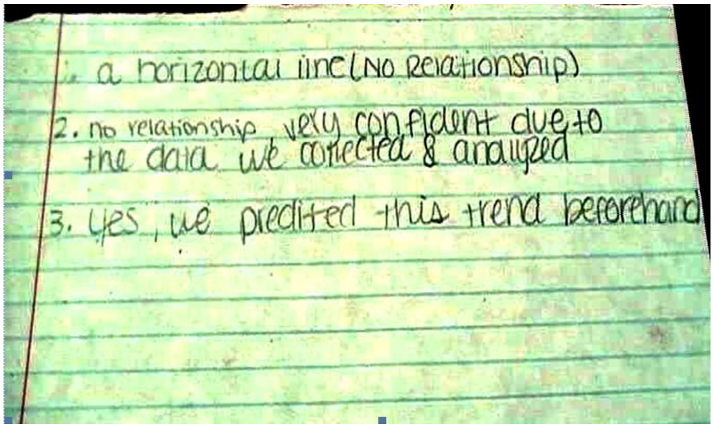
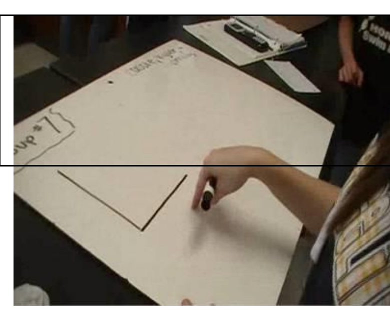


Figure 5.2.19. (a), (Day 4). Three questions assigned to teams concerning their experiment's data. (b), (Day 4, 20:50). Focal group's answers to the questions listed in (a).

1. In reviewing your data, describe what you expect the graph to look like (i.e., is your dependent variable changing?)?
2. Do you think there is a relationship or not, and how confident are you?
3. Does your data/trend make sense? Is it what you expected [before conducting the experiment]?

Kevin used the graph's axes to make sense of and support their choice for what to plot on the x-axis in Unit 5 when he stated, "it has to be a horizontal line." He was connecting his non-covariant expectation for the graph's shape to what would be necessary to produce it given this particular context. He contrasted his suggestion to the alternative in which the resulting graph would exhibit a vertical instead of a horizontal line.

1	Katie:	So which one did we, y depends on x [*points to the y- then the x-axis as pictured to the right*] so which one did we—
2	Addy:	—we chose—



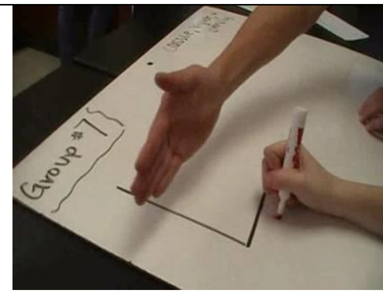
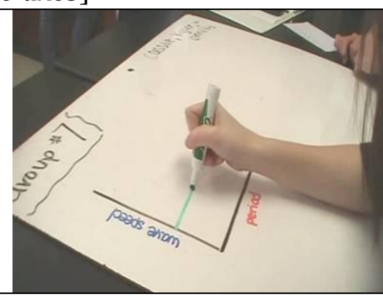
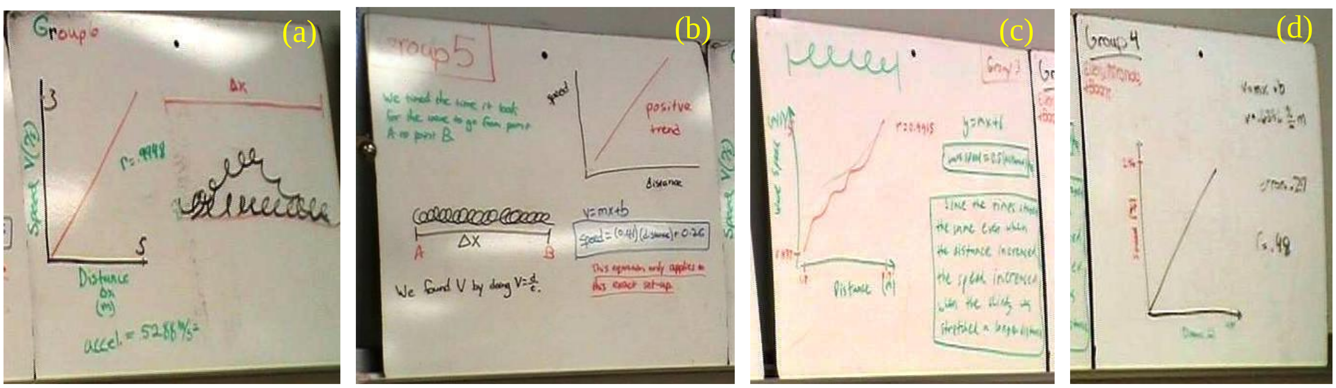
3	Katie:	—choose? [*3 second pause*] We would've chosen probably the period.	
4	Addy:	Yeah how fast I move my hand	
5	Kevin:	Yeah period is on the x-axis, [*says in agreement*] It also makes sense 'cause the wave speed was constant so instead of doing a straight vertical line, [*gestures as if to draw a vertical line on the axes*] it has to be like a straight horizontal line [*gestures with a flat hand pictured to the right to represent the horizontal line*]	
		[*pause in the discourse as Katie labels the axes*]	
6	Katie:	Ok so it's going to be a straight line [*thinks aloud as she draws a horizontal line onto the free-hand graph*]	

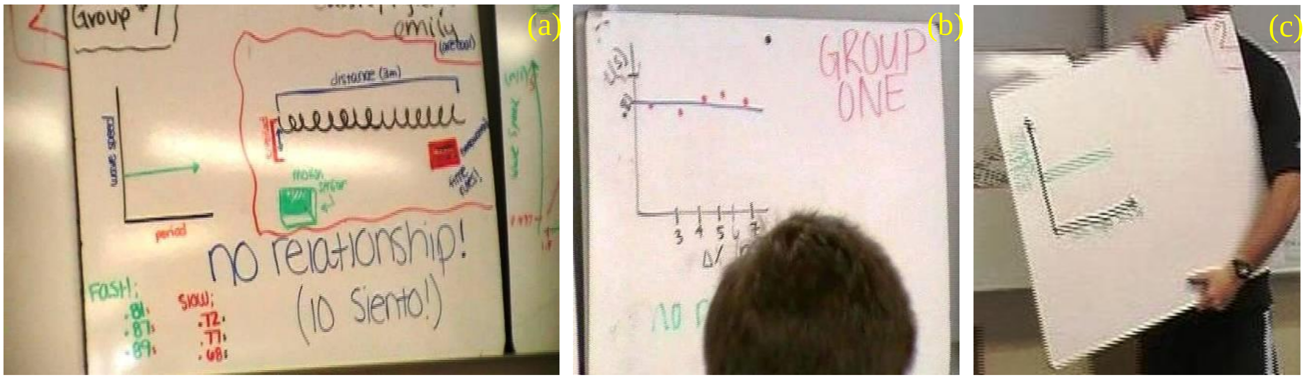
Figure 5.2.20. (Day 4, 25:17-26:20). Transcript of the focal group drawing a free-hand graph of their data for the second slinky experiment.

Once all of the groups had completed their whiteboards that summarized their results, we had a whole-class discussion about them. Since each half of the class conducted a different experiment, we first discussed those boards summarizing the slinky length versus wave speed experiment, followed by the period versus wave speed experiment. The whiteboards related to the slinky length versus wave speed experiment are shown in Fig. 4.2.6a-d. Examining the shared features of these groups' free-hand graphs provided me insight into my students' graphical grammar for free-hand graphs. All of these groups seemed to have correctly identified a covariant relationship, and have produced computer-generated graphs that had offered them the regression information they included in their free-hand graphs. All free-hand graphs had the same variables plotted on the x- and y-axis, and had both axes labeled with the quantity and its units. Moreover, all groups with the exception of the group whose board was pictured in Fig. 4.2.6b listed the maximum value on each axis to provide some degree of scale. These features were also present in the free-hand graphs of the remaining three groups who conducted the other slinky experiment (wave speed vs. period) shown in Figures 4.2.7a-c.



Reproduction of Figure 4.2.6. (Day 4, 34:30). Student-groups' whiteboards for the wave speed vs. slinky length experiment. In (b), the text accompanying the diagram is as follows: "We timed the time it took for the wave to go from point A to point B."

Every group who conducted the period versus wave speed experiment also correctly identified the canonical relationship, which was non-covariant in this case. The zero-slope best-fit lines in their free-hand graphs could not be derived directly from a computer-generated graph, since the regression had produced a slight positive or negative slope due to the relatively small number of data points the teams collected because of the time constraints imposed on them during this experiment.



Reproduction of Figure 4.2.7. (Day 4, 41:12). Student-groups’ whiteboards for the wave speed vs. period experiment. (a) Focal group’s board.

The group whose whiteboard is shown in Figure 4.2.7b sketched a zero-slope best-fit line, but also was the only group that drew data points onto their free-hand graph, which was not a common practice in my classroom. Including data points conveys that the data do not align perfectly with the horizontal line. Since the group concluded that there was “no relationship,” which was written on their board, and drew a zero-slope line, the data points drawn onto the graph were likely aimed at explicating how error affected their data as represented in the graphical modality.

During the whole-class discussion on the results from both experiments, I asked for volunteers to present to the class what their team had found. These presentations showed how students constructed meaning as they transduced between modes, diagrams, tables, and free-hand graphs. Brian explained his group's whiteboard (that presented results from the slinky length versus wave speed experiment) with the help of a laser pointer as shown in Figure 5.2.21. He used the laser pointer to make deictic gestures to the whiteboard presented in front of the class from his seat as he explained (Unit 1, Fig. 5.2.22). Brian started his explanation by stating his group's conclusion (i.e., that there was a positive trend), and then proceeded to justify this conclusion. His group's free-hand graph was simple yet effective in foregrounding the direct relationship. The best-fit line was already a prominent characteristic in the free-hand graph; however, Brian and his group emphasized it further by giving the best-fit line its own color (red) and adding the text, "positive trend" next to it also in a red color. He justified the relationship by stating the numerical values within the plotted dataset (Unit 1, Fig. 5.2.22). Although his whiteboard did not display the number tables, he alluded to the tabular modality by referencing individual values from it that were not included on the whiteboard or within the free-hand graph. He attempted to justify that changes in the speed (dependent variable) were too "scattered" (or large) to be a consequence of random error alone. Although there was no data table available on his whiteboard, his speech called for everyone in the class to envision this modality by his reading off some of his group's speed measurements. His reason for reverting back to the numerical or tabular modality was to justify his team's decision that this was in fact a covariant, and direct, relationship and not a non-covariant relationship like in the previous experiments. It was especially significant that he chose to refer to a table that was not publically displayed in front of the class as the free-hand graph was. Also, the graph lacked scale and, therefore, his reference to a large range of speed values had to be imagined too. Based on this discourse excerpt, Brian understood not only how to use data tables to identify potential non-covariant relationships, but also how to transduce between tables and graphs to describe a relationship between datasets.

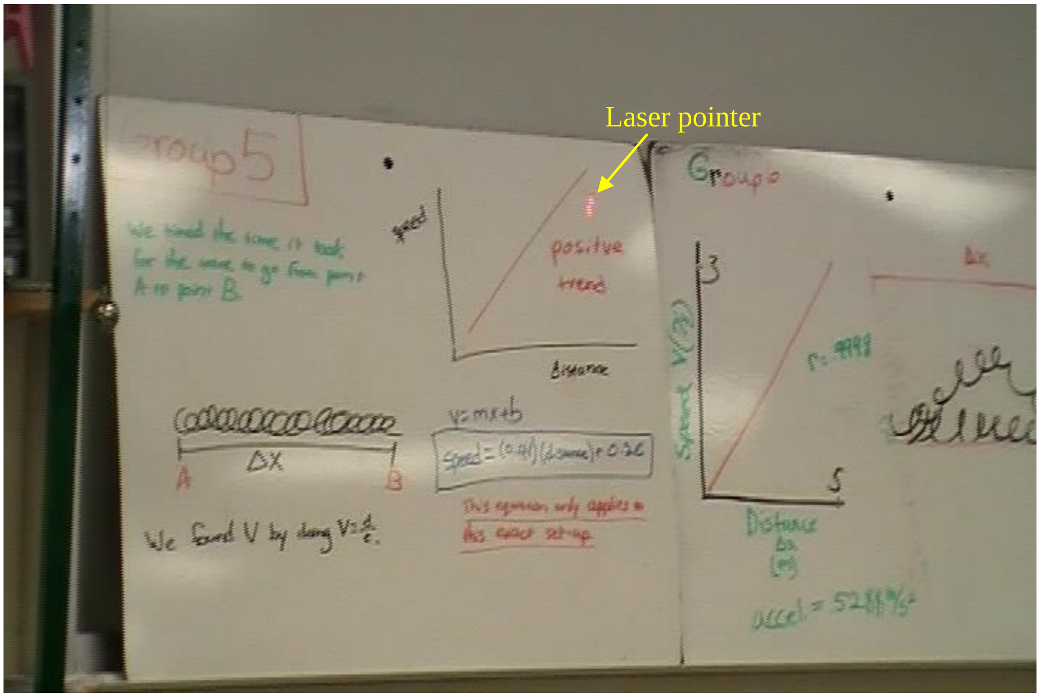


Figure 5.2.21. (Day 4, 34:57). Brian explains his group's whiteboard summarizing the wave speed vs. slinky length relationship to the rest of the class with the help of a laser pointer.

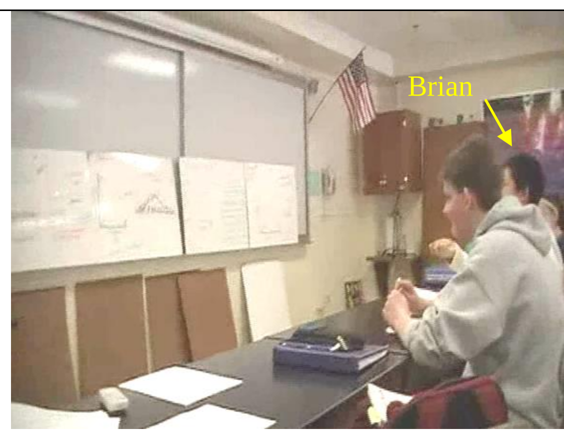
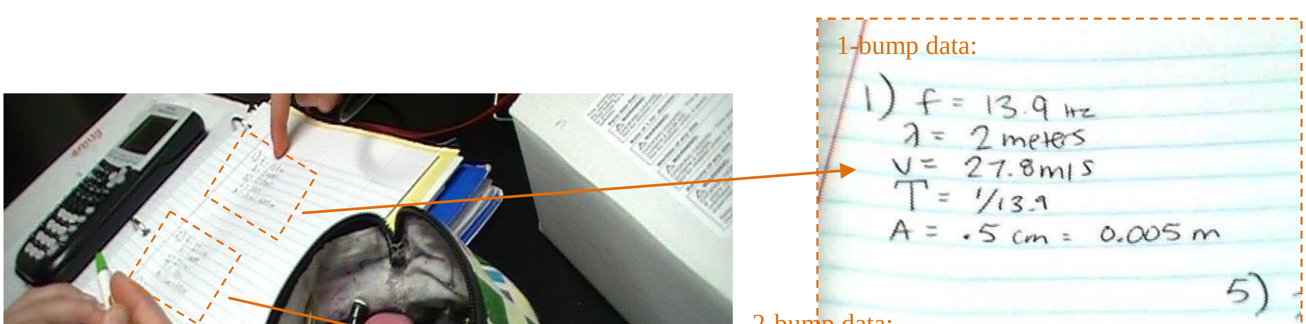
1	Brian:	We graphed it and we concluded that it was a positive trend [*see whiteboard shown in Fig. 5.2.21*] because um, our um, a lot of our points were really far, like they were really um scattered, like one was like .89, and then one was like 1-point-something, and then 2-point-something, and there was a 3-point-something, so we decided it was a positive trend. And we did this over a speed vs. distance graph.	

Figure 5.2.22. (Day 4, 34:53-35:21). Transcript of Brian's explanation of his group's whiteboard to the rest of the class.

Toward the end of the instructional unit (Day 11), students sought to discover patterns among several wave characteristics for standing waves, a new concept related to waves. They were given the task: “measure or calculate all possible wave characteristics for standing waves with 1, 2, 3, 4, and 5 bumps” [or antinodes]. In taking measurements on multiple standing waves, students were able to engage with the patterns related to wave characteristics that they had just learned about but not in the context of standing waves. I informed students that the point of the activity was for them to notice any patterns that emerge among the different standing waves.

During the activity, Addy noticed a pattern in the frequencies that created standing waves after recording the data from the 1-bump and 2-bump standing waves (Fig. 5.2.23), and suggested it to the rest of her group (Unit 1, Fig. 5.2.24). Recording the data into a table in her notebook might be why she was the first to notice this pattern, which suggests a possible benefit for students creating tables where they organize manually recorded data**.** As her group looked at her notebook, Kevin constructed a mathematical relationship underlying the pattern, suggesting in Unit 2 (Fig. 5.2.24) that, “you do 13 [Hz] times 3.” Here, 13 Hz was the frequency producing a 1-bump standing wave and 3 was the desired number of bumps (or antinodes). Recording and examining the data while being collected, and having to create more “bumps,” encouraged the focal group to derive a relationship between frequency and number of bumps in a standing wave–the integer multiple of the frequency that created one bump yielded the frequencies that produced standing waves with the same number of bumps as the integer multiple used to calculate it.



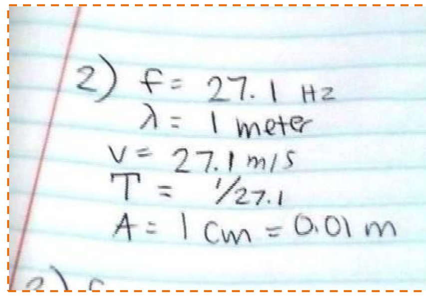


Figure 5.2.23. (Day 11, 24:22). The focal group examines the data from the first two trials in which they measured the wave characteristics of 1- and then 2-bump standing waves.

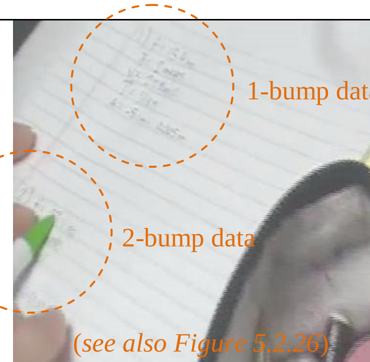
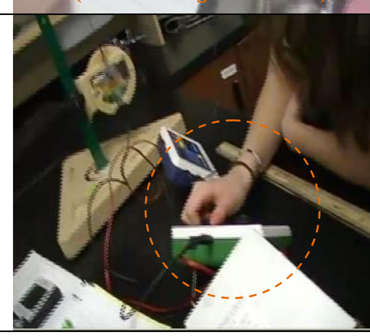
1	Addy:	So let's see, wait, for one wave it was 13, [*points to the 1-bump data set. A clearer picture of the data she is refering to is shown in Fig. 5.2.26*] two waves it was 27, [*points to the 2-bump data set as pictured to the right. A clearer picture of the data she is refering to is shown in Fig. 5.2.26*] three waves? What should that be? Somewhere in the thirties?	
2	Kevin:	It looks like it's doubling by 2, twenty-seven, so if you do 13 times 3 it should be around 39 or 40 Hertz [*Katie increases the frequency to 40 Hz as pictured to the right*] Uhp! I see three [bumps]!	

Figure 5.2.24. (Day 11, 24:12-24:40). Transcript of the focal group creating standing waves of 1, 2, 3, 4 and 5 antinodes while measuring the wave characteristics of each.

During both slinky experiments, and the standing wave activity, the focal group observed relationships among their data *while* collecting the data. The underlying relationships in all these activities were linear albeit with a zero slope in both slinky experiments. These relationships (i.e., the non-covariant trends that Katie and Addy had earlier observed for the velocity values during the slinky experiments and the covariant trend of the *integer-multiples* pattern for standing waves that Kevin was now suggesting) were inferred while using a data table. As students collected data for standing waves, they recorded their values in a table in their notebooks, and the focal group's data tables are shown in Fig. 5.2.25. As discussed earlier, the prominent feature of data tables are the individual values or measurements, and this may have encouraged students to *discover* patterns and relationships between these numbers. In their data table, students simultaneously tracked five different wave characteristics across each of the standing waves, which might be possible yet challenging to accomplish using graphs.

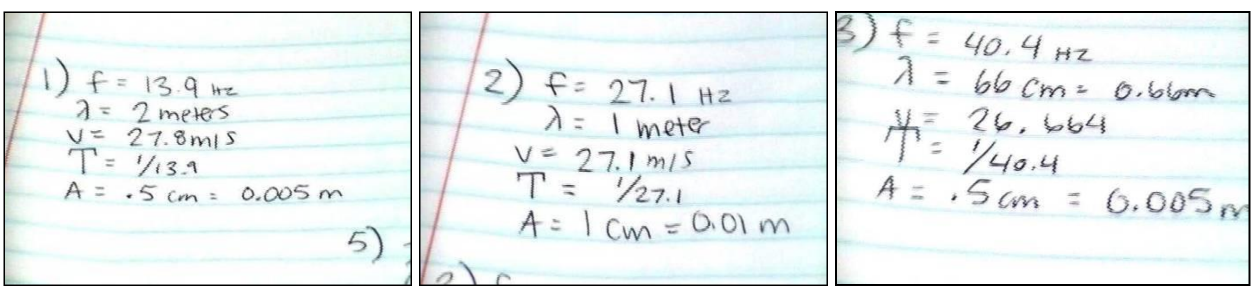


Figure 5.2.25. (Day 12, 27:58). Focal group's measurements of wave characteristics of 1-, 2-, and 3-bump standing waves.

Analyzing data while collecting them also afforded students the opportunity to test their emerging theories as they continued to collect data. As students tested their theories, they tried to predict the measured values for the next measurement, which could verify or refute a particular pattern. In Unit 2 of the transcript in Fig. 5.2.24, Kevin used the pattern he noticed to predict the frequency of a standing wave having 3 bumps. Katie then set the frequency to his predicted value and they observed that there was in fact a 3-bump standing wave, which supported his idea.

Despite the potential benefits of “in-the-moment” data analysis, a teacher promoting this type of engagement must be careful of students’ observer bias. When students have noticed a pattern, how might they respond if their expectation does not match the measurement? Students’ premature identification of a trend in their data when limited data have been collected might lead to biasing the data collection process in light of a possibly inaccurate expectation. If students apply reasoning appropriate for a dataset to an individual data point, they might choose to include, or exclude, new data points based on how these fit or not with their expectation, which could lead to observer bias and inappropriate conclusions. There was no evidence that as the focal group identified potential relationships while collecting data, they biased their dataset in any ways.

Moreover, as Addy recorded her group’s data from the 3-bump standing wave shown in Figure 5.2.25, Katie noticed another trend in their data. Addy read the calculated velocity value of “26.664 [m/s]” and Katie shared both a pattern and a justification for it “the velocities are all the same because you’re not changing the medium!” Katie’s statement was significant since it not only suggested she had recognized the constancy of velocity among all of the standing waves, but that she had made meaning of this pattern in relation to a primary concept she had developed from the slinky experiments, namely that a wave’s speed is only dependent upon the medium in which it propagates. Katie was able to apply this concept to a new context (i.e., standing waves) demonstrating her understanding of this concept. Several minutes later after they finished the experiment, Addy said, “the velocities stay the same because the medium isn’t changing,” which was the same idea Katie had stated earlier. Addy’s restating of Katie’s earlier interpretation suggested that this idea was now part of their collective conceptual understanding.

Summary

Students’ ability to choose the most appropriate modality, utilize their understanding of a mode’s grammar, and transduce between modalities, all shaped their ability to derive empirical relationships from tables and graphs that were aligned with the ones that are scientifically accepted. Students engaged with numerical data arranged into tables and plotted them on graphs via computer software and free-hand sketches in order to determine relationships among wave characteristics. The prominence of individual measurements in tables and the curve’s shape in graphs enabled students to engage with their data in many ways as they experimentally sought to discover these relationships. Students analyzed their data both in the midst of collecting them and after data collection was completed. They considered their data as individual measurements and as part of a larger dataset, interpreted the random error in datasets, assessed and applied that error to empirical relationships among datasets, and differentiated between covariant and non-covariant trends. Each of the modalities students utilized to engage with their data followed a unique grammar that my students and I developed discursively throughout the unit. Transduction between modalities was critical for students to develop conceptual understandings of relationships as different modalities afforded students different opportunities for meaning making.

My students took measurements during their data collection, which they organized in tables (Fig. 5.2.1 & 5.2.2). The units of these measurements became critical to the meaning students made of these numerical values (Fig. 5.2.4). Students’ engagement with units in single measurements, or in a dataset organized into a table, or in variables within mathematical equations, offered students opportunities to relate data points to each other or to other quantities via mathematical calculations.

The units of quantitative measurements also mediated a link between numerical values in a table and other modalities such as diagrams and graphs that may or may not have quantitative features. A student who knows how to procedurally engage in a modality may arrive at a correct answer, but may not have grasped the conceptual meanings within that modality or across other modalities. Students who can engage with and reason based on their analysis of both a number's value *and* units, can defend arguments, make connections, determine answers, and justify relationships. The focal group's analysis of their data following the first slinky experiment in my class developed and shared conceptual understandings as they analyzed their numerical data by first organizing them into tables. The group's collective interpretation of the relationship that governed their data (Fig. 5.2.5) emerged from reasoning about data points in their data table attending to both values and their units (Fig. 5.2.4).

Moreover, examining data while being collected as opposed to end of data collection afforded students more meaning-making opportunities. As the focal group interpreted their data during data collection, they were able to identify possible patterns and infer expectations, and then test their expectations as they continued to collect data. Tables, instead of graphs, offered students the opportunity to do this for five different variables simultaneously.

Students generated graphs by either graphing using software or by drawing free-hand sketches. Each provided particular benefits and limitations regarding student understanding of relationships among wave characteristics. Computer-generated graphs were quantitative, having scaled axes that students could manipulate, but they were automatically scaled to fit the data points. Line segments were also automatically connecting these data points but the software also performed regressions for students (e.g., Fig. 5.2.7a & 5.2.15a). These features presented both benefits and limitations to my students when using graphs as a modality for engagement.

Auto-scaling and connecting lines between points were features that, when coupled together, often misguided my students' development of appropriate relationships between the independent and dependent variables. This was especially the case for non-covariant trends in which the graph was automatically scaled over only the range of the available data, and the connecting lines created a shape or curve that students tended to interpret as a covariant relationship. In addition, linear regressions performed by the computer would always result in a nonzero, although very close to zero, slope, due to error that is larger when there is only a small number of data points, which also added to the potential for student confusion (Fig. 5.2.8 & 5.2.11b).

Although these features were often points of confusion, there were several beneficial aspects of computer-generated graphs: freedom to adjust and rescale the axes, opportunity to acquire numerical information from the regressions, and possibility of taking quantitative measurements related to wave characteristics. Students re-scaled the computer-generated graphs to better resemble their expectation of a zero-slope best-fit line that agreed with the empirical relationship they inferred from their data tables (Fig. 5.2.7b, 5.2.8, & 5.2.18). However, re-scaling to a larger range of y-values could also turn out to be misleading in some cases where actual covariant trends would be represented by flat lines. Thus, re-scaling should not be approached as a graphical technique, but it rather needs to be considered in relation to inferences constructed from the actual data organized in a data table, which facilitates engagement with the concept of error.

With free-hand graphs, in contrast to computer-generated graphs, students either drew graphs that were transduced from their data table, or represented an abbreviated depiction of computer-generated graphs. Such graphs enabled students to sketch their own axes and best-fit lines with no plotted data (Fig. 5.2.5, 5.2.11, 4.2.6, & 4.2.7). This further foregrounded the shape of the best-fit line, which was the relationship I intended for them to construct, by reducing the details involved. Data tables and computer-generated graphs both typically display a large number of numerical values that need to be interpreted to understand the underlying relationships among the data. In graphs, best-fit lines represent such relationships. Although the software offered my students regression equations, lines were most prominent in free-hand graphs that my students sketched. Moreover, the lack of quantitative and scaled axes of free-hand graphs reduced the myriad of quantitative details to only those values students wished to foreground. Students had to make their own decisions in terms of which graphical elements to include as they were constructing their free-hand graphs. For my students, these included the maximum values on each axis and the slope.

The features and ways in which my students and I made and conveyed meaning through free-hand graphs constituted their grammar, which was a hybridization of the grammars for diagrams and graphs. More specifically, the grammar for the construction of free-hand graphs in my class consisted of those features my students and I considered important to include, and how these features were used to make meaning of the relationships among datasets. Individual conceptions of the free-hand graphical grammar discursively shaped, and were shaped by, the collective understanding that we were developed as a class during whole-class interactions such as presentations of groups' whiteboards following experiments and teacher modeling of free-hand graphs during post-experiment lectures. I not only modeled the features I wished for students to include in their own graphs, but also verbally described how each feature influences the interpretation of the graph's relationship (Fig. 5.2.11-13). As my students were creating free-hand graphs, and I was explaining the form and function of particular features of such graphs, the collective grammar of these graphs was being created in my class.

There was also a significant interplay between tables and graphs in terms of extrapolating relationships from data sets. For example, as the members of the focal group transduced from their data table (Fig. 5.2.4) to a free-hand graph (Fig. 5.2.5), they not only constructed their understanding of the underlying relationship between wave height and wave speed, but also strengthened their understanding of the grammar of each of these modes. Tables afforded students to view data as individual points, and calculate a value for error that could also be used to differentiate between covariant and non-covariant trends in their data. However, tables did not easily allow students to identify the particular covariant relationship (e.g., linear, quadratic, etc.), and could not provide quantitative information about the relationship, such as regression values. Students could review a data table and recognize that the values were getting larger, for instance, but they may not as easily determine whether the points were increasing in a particular way by merely looking at the values in a table.

The focal group's free-hand graph in Figure 5.2.5 depicted the relationship they had determined from their data table before graphing data on a computer. Their free-hand graph represented their transduction between the tabular and free-hand graphical modalities. Had the focal group not already engaged with their data table to assess the error in their dataset, it may not have concluded a non-covariant relationship, a common mistake made by other groups (Fig. 4.2.2b, c). The non-covariant relationship these students inferred from their data table, in addition to their understanding of the graphical grammar, further promoted their adjustment of the scale in their computer-generated graph so that the best-fit line appeared flattened.

A key to students' success in understanding relationships among wave characteristics was the sequence of their transduction between modes. Students had to interpret—calculate and apply a value for error, from their analysis of their table of repeated trials to the changes in dependent variable dataset to determine if there was a covariant or non-covariant trend. Students needed to first engage with tables, which emphasized the individual points for students to analyze. Students avoided a potential point of confusion that arose from graphs, which reduced the level of inference that the tables afforded. The computer-generated graph represented the empirical relationship within a graphical mode that allowed students to create a free-hand graph with little engagement with the underlying relationship. In contrast, a free-hand graph of the empirical relationship from a table forced students to infer its shape (or relationship) in light of their analysis of the individual values in the table.

Once students used tables to identify the relationship as covariant, they constructed a computer-generated graph with scaled axes and obtained quantitative information, such as a regression information, all of which helped them to create a subsequent free-hand graph depicting it. When they identified a non-covariant trend, graphing with a computer was unnecessary and even misleading in some circumstances, especially if the computer-generated graph's relationship did not appear to agree with the one they inferred from their data table.

Students learned a sequence for analyzing data across various modalities. They understood the motivations for the transduction and could apply it and adapt to a particular experiment. For example, the focal group determined the first slinky experiment to have a non-covariant relationship using the tables, but still elected to graph the data using the computer. This unnecessary step might have been done in accordance to the group's perceived expectation for how experiments were to be conducted based on their experiences leading up to this unit, in which they often graphed data using computers. For the second experiment, they recognized that the computer graph was unnecessary, and did not create it. Students' choice of which modality or modalities to engage with relationships, how they utilize those modalities, and the transduction between modalities, were all integral to their understanding of relationships among wave characteristics, as well as how to derive them from experimental data.

VI. DISCUSSION AND IMPLICATIONS

This study explored multimodality in my classroom during an instructional unit on waves with regards to students' concept development and engagement with each other within and across modalities, or modes. Specifically, I investigated: How different modalities promoted and challenged students' concept development and interactions among classroom members, the circumstances and ways in which students and I called upon different modes, and how we used the grammar of modalities throughout the unit.

A variety of modalities were present and intentionally used in my classroom that included linguistic and non-linguistic modalites such as diagrams and gestures, which were prominent in my classroom's multimodal discourse. These non-linguistic modalities did not just supplement text, but captured and developed student conceptions in ways linguistic modes alone could not (Jewitt, 2009; Kress & van Leeuwen, 1996, 2006; Kress & van Leeuwen, 2001). As students developed conceptual understandings using different modalities, they also developed their abilities to make meaning and articulate ideas using those modalities. Students' conceptions of the grammar (form and function) of a particular mode were co-developed together with both the concepts and ideas, and the grammars of other modes. Each mode did not develop meaning in isolation from each other; instead, the intertwining, transduction, combination, and hybridization of modes offered powerful opportunities for meaning making.

Co-construction of Concepts and Grammars

Multiple modalities often occur simultaneously, but there are ebbs and flows to the prominence of a particular modality (Jewitt, 2009). The synthesis of multiple modes multiplies the meaning that students may construct and convey when compared to that of one mode alone

(Lemke, 1998). My students and I called upon various modes during our classroom interactions in order to construct and explicate meaning with each other, which in turn developed the grammars of those modalities. All modes, including gestures and diagrams that were tracked for this study, have their own syntactic and semantic rules and patterns (Lemke, 1990), or grammar. Kress and Van Leeuwen (2006) refer to *visual grammar* as the ways in which a variety of visual images communicate meanings. Since my students and I made a distinction between different visual images, such as diagrams and graphs, we developed and refined *diagrammatical* grammar as distinct from *graphical* grammar. As students were developing the grammars of the various modalities, they showed increased confidence and initiative to call upon modes whenever appropriate. To assign value as well as teach the grammar of gesturing and diagramming in particular, I modeled their use, lectured on what features made them effective, asked students to use them as part of activities, and provided students with continuous access and opportunities to engage with these modes on their own volition. Diagrams and gestures were often publically displayed in front of the whole class as focal objects during discussions. Their use and negotiation promoted the development of the collective diagrammatical grammar that was constituted by the individual students' conceptions and enactments.

Multimodality helped students to communicate their prior knowledge on the first day of the unit when they struggled to use speech alone. As they had not yet developed an academic language for talking about waves, gesturing and diagramming became pronounced modalities in my classroom's multimodal discourse. Non-linguistic modes become especially critical when students lack a shared linguistic system or academic language (Jaipal, 2009; Roth 2005). Students were able to speak colloquially about waves using everyday examples, such as water waves; however the wavy-line diagram and undulating hand gesture (UHG) that emerged on Day

1 both carried different opportunities for meaning making, or meaning potentials (Kress & van Leeuwen, 1996, 2006). The wavy line contained the hallmark sinusoidal shape of a wave that students later studied within waveform graphs, and whose specific qualities became visual representations of wave characteristics (e.g., amplitude, period, frequency, and wavelength). Students did not initially associate the wavy line and UHG with any of these characteristics since they were not yet developed, which made these modes particularly fertile for the construction of these ideas. The evolution of students' meaning making of the wavy line and UHG within and across modes demonstrated a significant benefit to learning via multimodality. Diagramming and gesturing minimized the need for a linguistic definition of waves, and provided a multimodal scaffold for the development of wave characteristics and later transduction to waveform graphs. Since measuring wave characteristics was a fundamental practice I aimed for students to develop during this unit, the emergence of the wavy line as a familiar conception of a wave became a semiotic resource whose grammar was shaped discursively as students developed their conceptual understandings of waves and wave characteristics.

The UHG along with the back and forth hand gesture (BFG) came to represent what Wittmann (2002) refers to as a wave's *particle* model, or the back and forth motion of the source or medium as waves propagate through it. Initially, the UHG functioned with the wavy-line diagram to enact its undulating movement that students envisioned but could not represent using the diagram alone. The BFG shared the oscillatory motion aspect with the UHG, but also differed: the BFG represented a wave's source, but the UHG, with its sinusoidal shape, represented the back-and-forth motion throughout the medium as the wave traveled through it. The back and forth motion represented a family resemblance (Roth, 2005), which mediated a grammatical link between the two gestures that eventually combined them into a single hand gesture by the end of the unit. Therefore, both gestures were integral to students' conceptual development of wave characteristics, especially regarding amplitude, period, and frequency, whose values all depend on the way in which the wave's source moves. The students and I also used the BFG in conjunction with other modes to connect our actions and experiences in their slinky experiments with diagrams and graphs of waves. This was done, for example, as students called upon a brisk BFG to suggest that the hand's quickness, while generating a wave pulse, might affect its propagational speed, before they developed the concepts of period or frequency. I too called upon a BFG when I superimposed it over a diagram of a slinky experiment's setup to bridge the diagram with the students' actions regarding their manipulation of the slinky during their experiments. The semiotic bundling of these modes as we engaged with ideas facilitated both the development of these ideas (Azarello, et al., 2009), as well as the grammars of the modes in which these ideas were expressed and took shape.

Additionally, when these back and forth gestures were infused with some forward motion, the propagational motion of the pulse, or *pulse* model (Wittmann, 2002) was linked with the pulse's back and forth motion. This shift, or transformation (Kress, 2003), in the ways in which elements of a modality are used to make meaning, reflected students' understanding of the gestural grammar. The BFG began as an iconic representation of the production of a single stationary pulse in a slinky. It was later transformed as Brandon used it to represent one wave cycle (up and down) in relation to a waveform graph. Here, the BFG moved up and down and to the right as he traced along the graph to demarcate one wave cycle from a continuous train of pulses. Finally, on the last day of the unit, the BFG further transformed as it combined with the UHG. The focal group made back and forth hand gestures that undulated up and down while propagating away from a bobbing mass to envisage a wave propagating in the air by tracing its path in the air using the gesture. This gesture referenced their diagramming and graphing experiences with the wavy line throughout the unit regarding wave characteristics, and simultaneously enacted the particle and pulse models of the wave.

The grammars of modalities (e.g., gestures, diagrams, graphs) were co-constructed between the students and me as we used them in relation to different ideas and contexts. They also mediated students' development of new concepts and their reasoning in light of their prior knowledge and experiences. Period and frequency (i.e., hand-quickness while creating waves), transverse and longitudinal waves, amplitude, demarcation of wave cycles in a continuous train of pulses, and standing waves were all concepts for which students used, and benefitted from, multimodality to make meaning. As students appropriated, shared and articulated multiple ways for multimodal communication of ideas related to these concepts, they became better able to explicate and developed multimodal understandings of those concepts.

In the midst of many modes that students and I called upon throughout the unit, diagrams were especially prominent. Diagrams are often a valuable modality for learning because they can represent complex and abstract ideas that the author has to express and the reader has to interpret, which may or may not lead to the same meanings (Kress & van Leeuwen, 1996, 2006). Diagrams capture systems in ways that other modalities do not. Even in circumstances where students can explain their ideas using linguistic modes, diagrams offer different and unique opportunities for meaning making that provide additional information that might otherwise be left out. Diagrams often work simultaneously with other modes to synthesize and multiply the meaning being made as each mode represents an idea in a slightly different way (Lemke, 1998). In the previous example in which the focal group, on the last day, gestured in the air to envisage a wave's propagation, students were diagramming in the air in order to make visible the wave (and especially its propagation) that was not observable in this occasion.

A particularly valuable function of diagrams was representing spatial layouts and positioning of artifacts within experimental setups. Diagrams provided a focal object for whole-class discussions and mediated our negotiation of experimental practices and manipulation of artifacts symbolically. They afforded students time to consider artifacts when the artifacts were not accessible. For instance, Ryan's diagram that described his idea for an experimental setup for the second slinky experiment (shown in Fig. 4.2.4) allowed the class to discuss potential experimental practices in light of the artifacts and how they might manipulate or use those artifacts before actually conducting the experiment. When confronted with this new experiment, the students and I used diagramming to facilitate the construction of the actual setup (Zahner & Corter, 2010).

The process of drawing diagrams also benefitted students' learning. Construction of diagrams offered them opportunities to engage more deeply with a phenomenon (Baldry & Thibault, 2005), since it entailed making decisions about which particular details from their observations to capture or not in their diagram, which is part of diagramming's epistemological commitment–the obligations that users of a mode face given its nature (Kress, 2003; Bezerman & Kress, 2008). For example, the group whose whiteboard is shown in Figure 4.2.14c, diagrammed the interference between two wave pulses in a slinky with opposing amplitudes, and had to choose which instances to capture with a diagram. These choices required students to not only identify critical moments, but also to consider *why* these moments were critical. Moreover, constructing a diagram of these instances forced students, for example, to show *how* or the ways in which the amplitudes changed instead of merely stating that they had changed.

The previous example also highlights potential limitations of the interpretive flexibility of any modality (Roth, 2005) including diagrams. In this example, students constructed diagrams based on their observations of two waves interfering in order to capture critical instances of evidence with which they could justify their conclusions. The diagrams in this case functioned as a resource for students' reasoning, which was made public when they produced it on a whiteboard and displayed it in front of the class. However, every modality carries meaning *potentials*, not meanings (Kress & van Leeuwen, 1996, 2006), thus offering interpretive flexibility to both authors and readers. The students and I were able to narrow the interpretive flexibility in diagrams by including captions, labels, arrows, and brackets. These characteristics of diagrams helped ensure similar interpretations between authors and readers of diagrams.

Students' ability to utilize modalities both shaped and was shaped by their engagement with ideas, one another, and the grammars for those modes. The prominence of a mode in a multimodal discourse depends on its cultural value and syntactical understanding of the participants (Kress & van Leeuwen, 2001). Students and I called upon different modes to position our thinking, negotiate ideas, express conceptions, and justify claims, which over time, assigned discursive value to those modes. Diagrams, for example, were a particularly protrusive mode in the discourse. As students came to value and understand how to use diagrams as an effective mode for meaning making, their initiative to call upon diagrams was strengthened. Moreover, the diagrams students produced reflected their practices, values, norms, beliefs, and actions, which were all interwoven into our classroom's multimodal Discourse (Gee, 1996). Diagramming became a part of our class' culture for doing science as students and I increasingly used them as a mode for developing and communicating concepts.

Prain and Waldrip (2006) considered learning to be evidenced by students' ability to represent ideas between and across different modes. In this way, diagrams may offer a window into the author's conceptual understanding (Cheng, 2009). They provide teachers and researchers a conceptual snapshot of what a student knows at a particular moment, which may include multiple representations including but not limited to diagrams (Waldrip & Prain, 2010). I was able to both access and assess Zack's understanding of standing waves at this moment based on his speech and gesturing as he attempted to draw a diagram with his hands in the air (Fig. 4.1.16). Zack lacked the physical semiotic resources to produce a diagram until I asked him to draw one in front of the class (Fig. 4.2.15). A potential limitation of this example, as an isolated event, is that it cannot account for the ways in which multimodality prepared and enabled Zack to construct meaning about standing waves using the diagram that he envisioned. Many further insights to be gained from this example are brought to light when it is considered in relation to the many multimodal interactions in the classroom within and across modes, and development of the grammars by me and the students.

Conceptual understanding and the grammar of the modes in which it is developed and communicated evolve together. It is therefore critical for science education researchers interested in how students develop concepts to consider the development of both the ideas and the grammar of the modes in which these ideas take shape. Ideational development is achieved interpersonally through multiple modalities, each of which carry syntax and semantics that constitute its grammar. Just as ideas change through discursive interactions and practices, so do the interpersonal and grammatical practices used to negotiate and shape them. Using diagramming again as an example, it could therefore be considered as a process for conceptual development instead of as a means for accessing and assessing one's conceptual understanding. Similar to

Lemke's (1990) and Roth's (2005) claim that as a student's ability to "talk science" increases with their learning of science, students developed their abilities to diagram as they developed a conceptual understanding of waves. In addition, as they diagrammed, wave concepts were shaped and developed by the epistemological affordances provided by the diagrams (Bezemer & Kress, 2008; Jewitt, Kress, Ogborn, & Tsatsarelis, 2001; Kress, 2003; Kress & van Leeuwen, 2006). Using diagrams, students constructed an individual and collective understanding of *what* aspects of a phenomenon or event were important to depict, but also *how* to utilize semiotic resources to represent them with diagrams.

Sequence of Transduction Between Modalities

Students engaged with data tables and graphs to experimentally derive relationships between various wave characteristics. As students conducted experiments, their data interpretation, both during and after the experiments, was critical to their conceptual understanding of these relationships. Kress (2003) pointed out the importance of transduction between modes to the meaning-making process. In addition to transduction, the sequence or order in which students transduced was especially important for them to develop concepts, such as wave characteristics and empirical relationships among them. In the latter case, their development of an empirical relationship using tables influenced the way in which they developed and interpreted it within the graphical modality (Wu & Krajcik, 2006). More generally, the sequence of transduction between modalities relates to concept development, which is significant to our understanding of teaching and learning, and warrants further exploration.

Students' engagement within, and transduction among, modalities evolved collectively as they converged upon a process for multimodal communication that ultimately characterized what it meant to do science in our class. As students transduced among modalities, each mode afforded unique meaning-making opportunities that contributed to the collective meaning and the development of the idea (Bezerman & Kress, 2008; Kress, 1993, 1997). However, the sequence of students' transduction represented a learned practice that they developed discursively throughout the unit. Moreover, they demonstrated an understanding by choosing an appropriate modality for a particular situation, and how to build upon the meanings developed from prior modalities. Students' ability to express an idea across many modes reflects their conceptual understanding (Prain & Waldrip, 2006). Therefore, choosing appropriate modes for engaging with an idea demonstrates not only student's understandings of the grammars of those modalities, but also their understanding of the ideas they express via those modes.

The students in my class converged upon a particular order of transduction from data tables to graphs that enabled them to derive empirical relationships that agreed with the scientifically accepted ones, and more specifically to successfully differentiate between covariant and non-covariant trends. Students often struggle to identify non-covariant trends among data sets (Kanari & Millar, 2004). Tables afforded students the opportunity to examine the data as a list of individual numerical values. Tables backgrounded the precise relationship (i.e., the trend of the relationship), and allowed students to consider the changes in the data as either due to random error (non-covariant) or due to a "real" difference in the dependent variable (covariant). Students who engaged with data tables first were able to engage with graphs in more meaningful ways. The ideas and empirical relationships they developed using the data tables, afforded them an expectation for the empirical relationship they would construct within the graphical mode. This allowed them to engage with the grammar of graphs in meaningful ways, such as re-scaling the axes transform a computer-generated graph in a way that allowed them to infer scientifically accepted relationships, which were also similar to the ones they expected from the data tables. Students who expected a non-covariant trend from their engagement with the data tables were able to recognize that a small range exaggerated the appearance of a graph's curve and rescaled the axes for an accurate interpretation.

Students' level of meaning making was especially strong when they inspected their data table and inferred an empirical relationship. They estimated its graphical representation using a free-hand graph instead of engaging with a computer-generated graph in which they would not have to envisage the graph's shape since the computer-generated graph would do that for them. When students inferred an empirical relationship using a data table before creating a computer-generated graph that presented a different trend from the one expected, they had to reconcile this difference. Such reconciliation led them to further development of the graphical grammar that allowed them to manipulate characteristics of the graph.

It was difficult for students to approximate empirical relationships from graphs, which was necessary in light of limitations in the data, such as a small number of data points. Students struggled to coordinate empirical relationships derived from different modes similarly to the ways in which students often struggle to coordinate theoretical and empirical relationships (Varelas, 1996), especially for non-covariant trends. The interpretation of the empirical relationship from the different modes may be different. The relationship itself is an approximation, which may be more or less apparent in one mode versus another. Students demonstrated an ability to approximate the relationship generated more often when they had already inferred a relationship using a table to which they could compare.

A primary feature of a graph is the shape of a graph's curve that describes the empirical relationship that governs the data graphed. . The prominence of this grammatical feature is an affordance of graphing that is often beneficial to learning, but in some instances, such as non-covariant trends, may present a potential challenge to students deriving empirical relationships that are scientifically accurate. For instance, it is possible to approximate a graph's slope of 0.08 obtained from a regression to be zero, as the focal group did. However, since the computer-generated graphs used in my class did not include error bars, they lacked the epistemological commitment regarding consideration of error that the tables had for my students. When students did not engage with the concept of error to infer a relationship from their tables, they lacked an expectation for their graphs' shapes as they transduced to computer-generated graphs. This limitation compounded by the students' developing understanding of the graphical grammar made them particularly vulnerable when using computer-generated graphs. For instance, students who lacked both an expectation for a graph's shape, and knowledge of how to rescale axes that might be exaggerating the curve's appearance, often misidentified relationships.

The transduction from tables to graphs was also significant because students ultimately constructed a free-hand graph to capture the relationship they considered the data to follow. When students identified a non-covariant relationship while engaging with data tables, graphing with a computer was unnecessary, and could therefore be bypassed, which the focal group did during their second slinky experiment (wave speed vs. period). In such circumstances, students were able construct a free-hand graph of the empirical relationship from their data tables. A computer-generated graph would not add any additional information (e.g., regression information), and as previously discussed, may contribute to the misidentification of the relationship if the graph's and table's relationships do not appear to match. For covariant relationships, the computer-generated graph was necessary as it provided quantitative information from its scale and linear regression that students needed to transduce into the free-hand graph. The success of groups in conceptualizing non-covariant relationships, which presented a pervasive difficulty for students, was founded in their engagement with tables to construct a relationship before graphing with a computer. Graphing via free-hand graphs provided students an alternate modality to computer-generated graphs for non-covariant relationships, which acted as a mediator to their engagement with computer-generated graphs.

Combination and Hybridization of Modes

Throughout the unit, my students and I created an interwoven multimodal fabric where multiple modalities were used to communicate and create meaning. Students' engagement with one mode influenced the ways in which they called upon and utilized other modes. Moreover, in some cases, modes combined while retaining their individual grammars (combination), or blended together into new modes with their own grammar (hybridization). Examples include: the synthesis of the BFG and UHG, the diagram-photo-graphical combination, and the hybrid free-hand graphs (hybrid of diagrams and graphs).

The BFG stemmed from students producing waves in slinkies during experiments, while the UHG emerged from students' prior experiences with waves and water waves in particular. The BFG was combined with diagrams as I superimposed the gesture on top of a diagram of an experimental setup. The UHG was also combined with diagrams when students traced in the air waveform graphs projected on the screen in front of them, whose sinusoidal path shared a family resemblance with the UHG's motion. The synthesis of the BFG and UHG represented a *transformation* (Bezerman & Kress, 2008; Kress 2003). The meaning associated with each gesture transformed as they were synthesized into a single gesture, which afforded students the ability to produce iconic gestures of non-observable propagation of waves, such as waves propagating in air and standing waves produced by waves moving too fast to be observed.

The diagram-photo-graphical combination reflected a superposition of modes. In the lesson on Day 6, I transduced a photograph of a slinky with a continuous train of pulses traveling through it drawing a diagram and including labels on it. The relevant aspects of the photo (e.g., slinky's shape, hand's back and forth motion, and metersticks) were foregrounded by my drawings while other photographic details that were irrelevant to the lesson were left to the background. The superposition allowed for the diagram to connect to the reality captured by the photograph, while abbreviating its myriad details to only those I considered important and depicted in my diagram. The diagram's characteristics also resembled graphical features, which further transduced the diagram-photo combination to a waveform graph, which was introduced during this lesson. The superposition and combination of the modes allowed students to consider the new waveform graphs in light of the other modes. This promoted the retention and utilization of those modes since each mode still existed while a new mode was superimposed onto it.

Free-hand graphs were a prevalent modality used by students, and were a hybrid of diagrams and graphs. Diagrams abbreviate a reality through a family resemblance between the sign and its referent (Jewitt, Kress, Ogborn, & Tsatsarelis, 2001; Roth, 2005). In the diagrams produced in my classroom, these abbreviations took the form of arrows, brackets, labels, and captions. However, when a diagram of a graph was constructed, graphical features such as axes and best-fit lines also became diagrammatical characteristics. The free-hand graph's characteristics combined the brevity of a diagram with the graphical concept of prominence of the relationship between independent and dependent variables.

Implications for Practice and Future Research

The many insights that might be of particular importance to teachers and teacher educators can be summarized as *multimodality awareness*. Awareness of multimodality in a classroom and the ways in which it can shape teaching and learning can be very powerful to a practitioner. Multimodality-aware teachers consider multimodal aspects in their pedagogical planning, paying attention to the ways in which both they and their students call upon various modes and transduce between modes as they make meaning in the classroom. They also promote multimodality in action as they afford their students varied multimodal opportunities planned or spontaneous. A teacher may provide multimodal opportunities as part of the lesson's structure, but may also encourage students' own multimodal ways of engagement with the content. Multimodality is more effective when teachers monitor and support students' development of grammar rather than impose it upon them (Towndrow, et al., 2009). Modes should be available and accessible to students at all times for them to call upon so that multimodality becomes integral to both teacher's and students' engagement. The planned and spontaneous multimodal events should shape each other. As students begin to utilize modes, in particular ways, the teacher can promote their development of these ideas within these modes or scaffold their transduction to different modes. Multimodality awareness involves providing students access to multimodality, modeling grammars of various modalities, and facilitating transduction between modes.

Availability and Access to Multimodality

Availability and access to multimodality is critical to creating a multimodal discourse in the classroom. Omnipresent multimodal spaces in which students may call upon whichever mode they prefer or deem necessary is of particular importance. At any moment in which students are able to interact with each other or the teacher, they need to be in a space where modes are both available and accessible. The teacher does not have to require students to use various modes at all times, but should allow and encourage students to call upon various modes whenever they consider it appropriate. In addition to available multimodal spaces, students need to develop a grammar for each mode in order to gain confidence and strengthen their initiative to both call upon and engage with modes effectively, which will in turn promote those modes as prominent and effective ways for constructing and negotiating meaning.

In my classroom, for example, diagrams were a mode that was constantly available and accessible for students that they could chose to use at any time. As students develop a diagrammatical grammar, they also develop a means for communicating ideas that they can build on with increasing confidence. Students' developing competence facilitates the teacher-student sharing of control over ideas developed and modes used to develop and express these ideas. Zack, for example, during the standing waves lesson, envisaged a diagram and gestured as if to draw the diagram in the air with his hands, as he struggled to articulate his ideas in speech. I facilitated his diagramming by asking him to draw what he was envisioning on the screen projected in front of the class. Zack had already called upon a diagram, but lacked the physical semiotic resources, which I then provided. Since all modes involve materiality, Zack used his hands, instead of a pen or marker for example, when he initiated forming his diagram. Drawing in the air was not permanent, and not a physical medium, and therefore not an effective semiotic resource for communicating his ideas via a diagram. My request to draw it did not suggest diagramming, but simply offered Zack the physical semiotic resources he lacked in order for him to construct a permanent diagram.

I also supported student use of diagrams throughout the activities by continually asking them to display their team's findings on whiteboards. I did not explicitly require or tell students to diagram on these boards. The open canvas on the whiteboards and multiple-colored dry-erase markers afforded them the semiotic resources to draw diagrams if they elected to do so, which would then be shared with the rest of the class.

Modeling Multimodal Grammar

A teacher with multimodality awareness should aim at promoting students' use of various modes, which, in addition to continually providing students with multimodal spaces, consists of modeling the grammars of modalities for students. In my classroom, I hoped for students to take on the practices I suggested when engaging with those modes during future lessons. For example, I explained during a lecture how to use complete-dataset and repeated-trials tables to calculate and then apply a value for error to construct an empirical relationship before graphing with a computer. Students later enacted this during their experiments, which gave them an opportunity to further develop the grammar of tables. This example highlights the semantics component of the grammar, or the ways in which meaning is made using tables. However, modeling the syntactic aspect of a mode's grammar along with the semantic one is also critical. . For instance, in my classroom, I engaged students in incorporating arrows in their diagrams beginning early in the unit (e.g., Fig. 4.2.3).

It is also important for students to model grammatical practices for each other. During any form of communication, students are demonstrating grammatical aspects of the mode(s) they use. These aspects may already exist in the class' collective grammar for that mode, or may be new ones created by a student based on the needs or motivations for communicating in that mode. For example, the UHG emerged on the first day of the unit as a means for students to describe the sinusoidal shape of a wavy line and undulation exhibited by waves. As another example, the use of brackets in diagrams was suggested by students who wished to denote intervals. Both of these examples were student-generated aspects of a particular mode's grammar that were publically demonstrated and later taken on by other students during future lessons. Teachers can further emphasize these new and potentially fruitful grammatical aspects by marking their value and promoting further their usage.

Sequence of Transduction and Multimodal Lesson Planning

Transduction among modes is critical to teaching and learning via multimodality, and a teacher's careful planning and consideration of the sequence of transduction among modes may be especially important. The order in which modes transduced in my classroom influenced my students' conceptual development of wave characteristics. Multimodal superpositions (e.g., photo-diagram-graph combination, and my BFG superimposed over a diagram of an experimental setup) represent a simultaneous and transparent transduction among modes that teachers can enact in a particular order to help students layer a concept with meaning across modalities. Teachers who are multimodality aware may also recognize student confusion that may be manifested as an inability to transduce between modes. Such an inability may be due to a compromised understanding of an idea, or a lack of knowledge of the grammars of the modalities to be transduced, or a combination of the two.

Transduction should be explicitly taught. In my classroom, by teaching transduction as an experimental practice for analyzing data, students were able to successfully derive non-covariant relationships and justify covariant relationships empirically. This is particularly important when students experimentally derive non-covariant relationships. Experiments in which students are to discover non-covariant relationships are often aimed at dispelling student misconceptions. For example, it is common for students to believe that shaking their hand faster while creating a wave in a slinky will make the wave propagate faster. In conducting an experiment seeking this relationship, students found that, contrary to their expectations, the period did not affect the wave speed. Students incorrectly deriving a covariant relationship when it is canonically non-covariant could potentially reinforce the misconception instead refuting it (Bonner, 2012).

Directions for Future Research

There is much to be learned from educational research about the role of multimodality in teaching and learning of physics and other science fields. Students' engagement with multiple modes, and more specifically the role of grammars of the modes used to construct meaning represents a potentially fruitful area for future research. In what ways do the grammars of modes used by the teacher and students in biology, or chemistry, co-develop with students' conceptual understanding? There is little research that explores the development of both teaching and learning via multimodality; that is, how both the teacher and students multimodally develop their ideas together. In addition, this study suggests the importance of examining the development of the individual and collective grammars of prominent modalities and its interaction with the development of ideas and concepts. The reciprocal relationship between a modality's grammar and meaning affordances as they mutually shape each other over time is critical to understanding how concepts develop though multiple modalities.

The practices of transformation and transduction, and combination and hybridization of modalities, are also areas in need of further research, since, as discussed in the context of this study, they are highly situated and depend on the moment-to-moment interactions among students and teacher as well as the teacher's instructional plans. The many possible ways in which modalities blend together into combinations or new hybrid modes during teaching and learning, and under what circumstances and motivations they occur, is largely unknown. Moreover, researchers often consider modes as acting in isolation or simultaneously with other modes, but neglect to pay careful attention to the transduction among modes, and *sequence* of transduction in particular. For example, Kanari and Millar (2004) recognized the importance of students analyzing their data in tables as opposed to graphs when engaged with non-covariant relationships, but did not explore the transduction between the two modalities and the associated opportunities and challenges. Multimodality is also an increasingly prominent topic when considering the amount of technology-enabled modalities and the availability of many communicative modes beyond traditional linguistic ones. In addition, the students' confusion during the last activity of the unit regarding the BFG's depiction of a transverse versus longitudinal wave presented a potentially fruitful topic in need of further investigation. Since longitudinal waves were not a primary learning goal for the students in this study, the BFG as a mediational gesture between transverse and longitudinal waves was never fully examined. The present study offers insight, albeit not nearly enough, on how exploring students' transduction between modes can promote our understanding of meaning making processes, and demonstrates how it might be used as a fertile research construct in future studies.

Teacher research also afforded this study a unique perspective by positioning me as both a teacher and learner. As the teacher, I had an understanding and knowledge of the students, and access to and engagement with them, all of which offered affordances to me as a researcher. My research in turn influenced my teaching and the multimodality of my classroom's discourse.

Teaching as I simultaneously collected data, and having to consider my research while teaching, presented challenges, but were not as limiting as one might think. Most of the instances in which one would expect tension between research and teaching did not result in any conflict. For example, the need for students to elaborate for the sake of data did not seem to be at the expense of the lesson pacing or activity structure. As was true for this example and many other such instances, the common goals for both my teaching and research minimized any tension. In the previous example, elaboration of utterances benefited both the copiousness of the data for this study and the clarity of the exchanges within the classroom discourse in which students constructed conceptual understandings. Teacher research can provide unique opportunities and perspectives to important areas of research in science education, including but not limited to multimodality. The reciprocal relationship between teaching and research comes to the fore in teacher research, and the shaping of one's teaching from their learning through conducting a study is as important to science education as students' learning. Although not a direct focus of this study, it is evident throughout this manuscript that my teaching was informed by my research, and vice versa. Teacher learning from conducting teacher research might be profound in terms of developing high quality teaching practices that are based on science education research.

In closing, studying multimodality in the science classroom, especially in light of both teaching and learning, can provide a productive lens for future research. Better understanding the possible benefits and limitations of various modalities, the transduction, combination, and hybridization between modes, and how ideas co-develop across modes and their grammars may provide insights into the teaching and learning of any topic within physics and other scientific disciplines.

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APPENDIX

Outline of Instructional Unit on Waves

Day 1 – Lesson: ***Activate prior knowledge; draw & define waves***

- Students were asked to draw, define, and list examples of waves on a small 1 x 1 foot whiteboard.
- The whiteboards were displayed publically, and considered as objects of discussion.

Day 2 – Lesson: ***Slinky Experiment I – wave speed vs. wave height***

- The student-teams were given the purpose: graphically and mathematically represent the relationship between the wave height and wave speed for a single pulse in a long metal slinky.
- They set up the experiment, collected and analyzed data, and summarized their data on a large 2 x 3 foot whiteboard.
- Four out of the seven whiteboards were later displayed in front of the class to facilitate a discussion.

Day 3 – Lesson: ***Summary lecture on slinky experiment I; slinky experiment II & III – wave speed vs. period & wave speed vs. slinky stretching distance, respectively.***

- Teacher-led lecture summarizing the results from Slinky Experiment I
- The student-teams were then assigned one the two following purpose statements, graphically and mathematically represent the relationship between: (1) the period and wave speed, or (2) the slink's stretching distance and wave speed for a single pulse in a long metal slinky.
- Whole-class discussion in relation to how to measure period
- The students set up their experiment, and collected and organized their data.

Day 4 – Lesson: ***Finish slinky experiment II & III (analysis)***

- Students worked individually on a bell work in which they analyzed sample data and its error.
- Students then publically offered their responses to the bell work during whole-class discussion.
- In teams, students answered 3 questions guiding their analysis of their data collected the previous day
- Each team prepared a whiteboard of their results, which were juxtaposed publically during a whole-class discussion of each experiment—period vs. wave speed, then slinky stretching distance vs. wave speed.

Day 5 – Lesson: ***Summary lecture on slinky experiment II & III***

APPENDIX (continued)

Day 6 – Lesson: ***Wave characteristics – introduce waveform graphs; characteristics that can be measured***

- Demonstration in which Mallory created continuous waves in a slinky while a motion sensor recorded the back and forth movement of her hand. It plotted and displayed in front of the class, a real-time position vs. time graph using a computer interface.
- Also during this time, Zeke stood on a table and photographed the slinky from an above view.
- The position-time graph and Zeke's photograph were projected side-by-side in front of students.
- I drew over the photograph to make it appear as a vertical position vs. horizontal position graph.
- Students worked in teams to determine numerical values for any wave characteristics they could determine.
- We then shared our findings as a class during a discussion.

Day 7 – Lesson: ***Work in teams on practice problems***

- Students worked together on a set of practice problems.

Day 8 – Lesson: ***Each team whiteboards solutions to one of yesterday's practice problems***

- Small groups of students were each assigned one practice problem from a set of problems they had worked on during the previous day. They were instructed to prepare a large whiteboard of their solutions to their assigned problem.
- Each group's whiteboard was a visual aid for the randomly selected group member that was to explain the whiteboard to the class.

Day 9 – Lesson: ***Wave interference***

- In teams, students constructed experiments to answer each of the following questions:
  (1) Will waves pass through each other completely, do they bounce off completely, or a little bit of both?
  (2) How will waves' amplitudes be affected at the instant they interact--nothing, create a gigantic wave, completely destroy each other, etc.?
- Each team prepared a whiteboard summarizing their results that were then publically displayed and discussed as a class.

Day 10 – Lesson: ***Introduction to standing waves***

- A standing wave in an elastic string was set up in front of the class, and became the focal object for a whole-class discussion.
- In teams, students then created a standing wave and measure all possible wave characteristics

APPENDIX (continued)

Day 11 – Lesson: ***Standing waves activity***

- Student-teams set up standing waves in order to measure the wave characteristics for 1-, 2-, and 3-bump standing waves.
- In conducting the experiment, students noticed patterns among the measured characteristics, and in some instances, were able to predict measured values using the patterns.

Day 12 – Lesson: ***Mass-on-a-Spring Lab Practical***

- Each team was provided a vertically hanging mass-on-a-spring system about which each team member would be given a one-question oral exam later in that same lesson.
- Their task was to consider the bobbing up-and-down of the mass to be a wave source, and to use it to measure all possible wave characteristics.
- I allowed them interact with each other and the artifacts for 15 minutes in preparation of an oral lab practical.
- They took measurements and prepared themselves for any question I might ask them regarding their experimental setup.
- Afterwards, I went from group to group asking each team member one of three different questions about the experimental setup, such as “Explain to me the frequency of this wave source, and how would you make it have a higher frequency?”

VITA

NAME DAVID CHARLES BONNER

EDUCATION

2013	Ph.D	University of Illinois at Chicago	CURRICULUM & INSTRUCTION
2003	M.A.	Miami University	EDUCATION
2002	B.A.	Miami University	PHYSICS

EXPERIENCE

Teacher

Hinsdale South High School, 2004-present, Grades 9, 11, & 12, Darien, IL

Physics Team Leader

Head Coach: Girls' Track & Field, Asst. Coach: Boys' Football

Teaching Assistant

Miami University, Physics, 2002-2003, Oxford, OH

Research Assistant

Miami University, Physics, Bali, S., 2002-2003, Oxford, OH

Real-time differential refractometry without interferometry at a sensitivity level of 10^{-6}.

Miami University, Physics, Bali, S., 2001, Oxford, OH

Summer Scholars program, constructed the saturated absorption spectroscopy phase of a magneto-optical trap used in laser cooling and trapping of vaporous atoms. Magneto-optical trap was used to cool Rubidium-85 atoms down to 10^{-6} Kelvin.

Case Western Reserve University, Geochemistry, van Orman, J., 2003, Cleveland, OH

Studied cation diffusion rates in periclase (MgO) under high temperature and pressure (representing chemical transport at the core-mantle boundary).

AWARDS

Presidential Award for Excellence in Mathematics and Science Teaching, 2011 ($10,000 and honored at 3-day reception in Washington, D.C.)

Hornet Hero Award, 2007

PROFESSIONAL ACTIVITIES & AFFILIATIONS

Leader/Founder of Teacher Inquiry Program, Hinsdale South H.S. (2010-2013)
Leader/Founder of Math-Science Alignment Team, Hinsdale South H.S. (2008-2013)
Reviewer for *The Physics Teacher*
Member of NSTA – National Science Teachers Association
Member of ISTA – Illinois Science Teachers Association
Member of AAPT – American Association of Physics Teachers

PUBLICATIONS

Bonner, D. (2012). Are You Certain? Teaching error analysis and other experimental skills in the physics classroom. *The Science Teacher,* 79(3), 72-76.

Fullerton, D., & Bonner, D. (2011). Making Projectile Motion Come Alive: Forensic Investigation Day. *The Physics Teacher,* 49(9), 554-556.

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PRESENTATIONS

Bonner, D. (2013, April). *Bringing Forensics in Physics.* Presentation at the national meeting of the National Science Teachers Association (NSTA), San Antonio, TX.

Bonner, D. (2013, April). *Are you Certain? Teaching error analysis & other experimentation skills in the physics classroom.* Presentation at the national meeting of the National Science Teachers Association (NSTA), San Antonio, TX. Also presented at the national meetings of NSTA in 2012, Indianapolis, IN; and 2011, San Francisco, CA; and at the annual meeting of the Illinois Science Teachers Association (ISTA), in 2011, Tinley Park, IL; and 2009, Peoria, IL.

Bonner, D. (2012, November). *You are the game changer in STEM education! Teaching and the STEM initiative: making a difference through teaching in a country in crisis*. Presentation to the Miami University Physics Department as guest presenter for weekly seminar series, Oxford, OH.

Bonner, D. (2011, March). *Multimodality and Learning: Exploring concept development and student engagement in a physics classroom.* Presentation at the national meeting of the National Science Teachers Association (NSTA), Teacher-Researcher Day, San Francisco, CA.